

Assessing the Effects of Engine Load on Compression Ignition Engines Using Biodiesel Blends

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Abstract

This study evaluated the performance of a diesel engine operated with waste plastic biodiesel fuel (WPPO) blends. Findings were that at all engine loads (from idling to full load) the emissions of carbon monoxide (CO), unburnt hydrocarbon (UHC) and carbon dioxide (CO₂) were low compared to conventional diesel (PD), although the emissions of NO_x were higher. The brake specific fuel consumption (BSFC) for the blends dropped while the brake thermal efficiency (BTE) increased with load for all blends until intermediate load when it decreased. WPPO blends had a higher viscosity compared to PD. CO emissions for blend 95/WPPO5 at all engine speed idling modes were 285 ppm, 298 ppm, 320ppm, and 388 ppm while PD emissions were 270 ppm, 295 ppm, 315 ppm and 365 ppm respectively. The values for UHC for blend 95/WPPO5 at all modes were 35 ppm, 28 ppm, 22 ppm, and 18 ppm compared to PD fuel with 20ppm, 25 ppm, 30 ppm, and 40ppm respectively. The NO_x emissions for PD fuel at all modes were 175 ppm, 225 ppm, 300 ppm and 375 ppm compared to blend 95/WPPO5 at 195 ppm, 245 ppm, 335 ppm, and 397 ppm. The BSFC values for blend 95/WPPO5 at all modes were 0.48 kg/kW.h, 0.41 kg/kW.h, 0.35 kg/kW.h and 0.4 kg/kW.h compared to PD at 0.45 kg/kW.h, 0.39 kg/kW.h, 0.33 kg/kW.h and 035 kg/kW.h respectively.

Keywords: engine loads, emissions, higher viscosity, spray characteristics

1. Introduction

Development of alternative fuel energy began in the 1900s when German engineer Rudolf Diesel invented the diesel engine using vegetable oil [1]. However, due to availability of petroleum at the time the focus moved into fossil fuel to the disadvantage of bio-oil. Currently many researchers such as [2–7] have focused on development of alternative fuel to petro-diesel (PD). Most of this research is heavily biodiesel based as this is one of the solutions to replace fossil fuels while creating renewable and green fuels. Fossil fuels are non-renewable and are depleting rapidly, hence the need for large-scale research to find alternative and renewable fuels. Alternative fuels must prove to be feasible, environmentally friendly and sustainable while meeting a large energy demand [8].

Fossil fuels have a detrimental environmental impact [9] when released to the atmosphere due to the combustion activities of fossil fuels. It is being projected that if no measures are put in place by 2030 the use of fossil fuel will raise emission levels by 39% [10]. Besides environmental concerns, fossil fuels have erratic demand and

supply which increases international market prices and other commodities hence promoting inflation [11]. **Figure 1** shows measures taken as a way of combating environmental pollution from the transportation industry in the European Union by means of taxes and social contribution as a function of gross domestic product.

In order to determine the efficacy of biodiesel, mainstream researchers in biodiesel fuels have evaluated engine performance using different feedstocks and different biodiesel blends [13–16]. However, few have been able to investigate the influence of load using plastic waste oil blends of biodiesel [17–19]. All these researchers have concentrated on performance and emission characteristics with little attention to low load and intermediate load compared to engine full load [8, 20, 21]. For example, all low load and intermediate engine idling speeds are considered as high idling, and mostly increase emissions from trucks and vehicles in the transport industry.

High idling or low engine loads have been shown to increase NO_x emissions on roads compared to high speed road driving by a factor of 1.5 [22, 23]. In other words, increasing low load increases NO_x emissions [24–26]. During idling, which is low load, the fuel consumption as well as engine wear and maintenance increase. The average fuel consumption for example in trucks at idle is 0.8 g/hr. to 1.5 g/hr. based on the size of the engine, ambient temperature and the load of other systems such as HVAC and vehicle electrical loads [27]. This is when compared to driving cycle emissions of UHC that are 1–5 times more.

On the other hand, during low load other emissions such as CO rise to 295 g/hr. [28–30]. The carbon emissions during the driving cycles are estimated at 45–75%, while UHC emissions during idling and low load can reach 86.4 g/hr. [27, 31]. Most diesel engines typically spend a substantial amount of time in idling mode, either at traffic stops, checkpoints or in exchange periods in fuel stations. The idle time spent varies considerably with the many varied reasons for maintaining engines at idle. For long haulage trucks, for example, the most common reason is climate control, loading and offloading transport cargo or service and maintenance [32, 33]. The other reason why trucks idle for a long time is use of the engines to heat and air-condition cabs and to power amenities in the cab while on the road [34, 35].

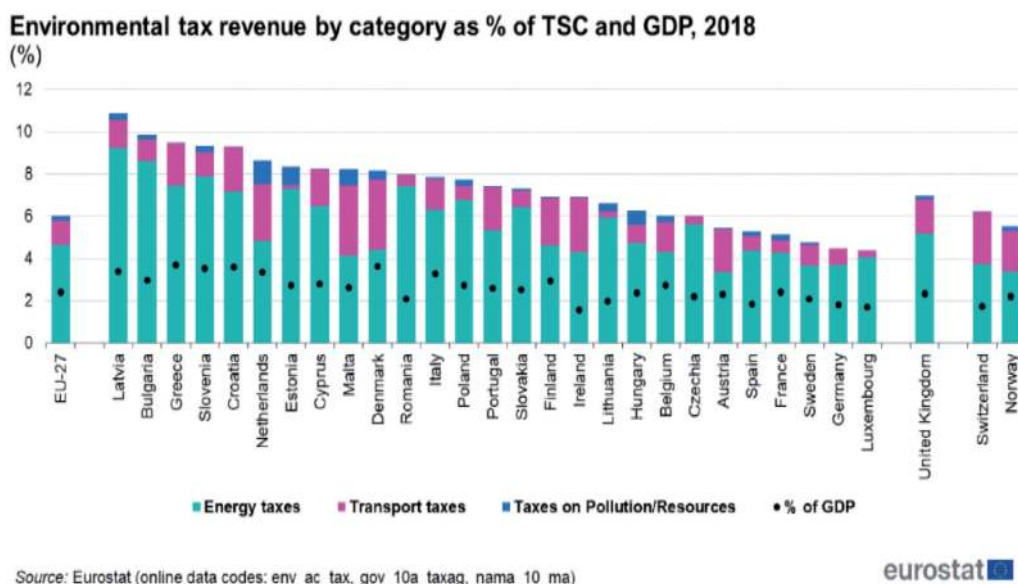


Figure 1. Environmental taxes as % of GDP and as % of total taxes and social contributions [12].

Biodiesel oil is known to contain physicochemical characteristics of functional PD properties [36, 37]. Research has shown biodiesel fuels have many advantages over PD. For example, biodiesels are biodegradable, non-flammable, renewable, non-explosive, non-toxic and environmentally friendly [38, 39]. These qualities show biodiesel fuels to be the best options to substitute for fossil fuels. Biodiesel fuels have a variety of feedstocks such as used vegetable oil, waste plastics, waste biomass, animal fats (tallow) and recently microalgae, all which can be processed into biodiesel [40]. Biodiesel has the ability to be utilized as a fuel with or without engine modification which gives it high technical advantage [41, 42].

The use of biodiesel and biodiesel blends affect diesel engine performance characteristics. Poor quality biodiesel fuel results in deposits and clogging [43, 44]. Besides these problems, use of biodiesel can result in corrosion, excessive engine wear and premature engine failure [45]. Biodiesel also causes deposits in the injector pump, which interferes with the spray pattern, an essential factor in mixing fuel during the combustion process, hence poor engine performance [46]. Other demerits, which are associated with biodiesel fuel use, include dilution of lubrication oil leading to high crank-case oil levels followed by loss of engine oil pressure and increased engine bearing wear. Thus, it is clear that the quality and testing of biodiesel is an important factor in ensuring proper rating, acceptance and durability of diesel engines.

The objective of this work was to use waste plastic pyrolysis oil (WPPO) and determine the effects of idling speed load-using blends of WPPO on a diesel engine. The second objective was to study the effect of brake specific fuel consumption (BSFC) of WPPO at low and intermediate engine conditions, also known as high idling condition. The third objective was to find the effect of engine load at high idling on engine performance and emission characteristics using WPPO as an alternative fuel.

2. Methodology and materials

2.1 Crude WPPO oil properties

WPPO was selected for this study because of the advantage of turning waste into energy to reduce the environmental impact of waste plastic. The second factor that informed the use of waste plastic is sustainability as waste plastic is readily available in municipal solid waste management sites. The plastics were collected from various holding facilities within the Durban metropolitan centres comprising a variety of plastics.

The pyrolysis oil was obtained from the pyrolysis unit in the Green Energy Group laboratory in the Department of Mechanical Engineering, University of KwaZulu-Natal. The author in his previous work covered the design of the unit and its performance analysis was published in the proceedings of the DUE 2019 conference in Cape Town [47]. The WPPO testing and measurements were conducted at InterTek, a private laboratory in Durban and the results are shown in **Table 1**.

2.2 WPPO biodiesel processing

A two-step process was used to process the WPPO as its acid value is higher compared to petroleum diesel. Therefore, an acid catalyzed process was used with the molar ratio maintained at 12: (50% v. v), 1% of H₂SO₄ was added to the preheated oil at 70°C for 3.5 hrs with a stirring speed of 400 r/min in a reactor of 5 liters.

	Unit	PD	WPPO
Density @ 20 °C	Kg/M3	845	825
K. Viscosity @ 40 °C	mm ² /s	3.04	2.538
Cetane number	—	55	—
Flash point	°C	50	43
Fire point	°C	56	45
Carbon residue	%	22	0.015
Sulfur	%	<0.028	0.248
Gross calories	MJ/kg	46.50	43.32

Table 1.

Properties of diesel and WPPO before processing into biodiesel properties.

Thereafter the products were put into a separating funnel and the excess alcohol, sulfuric acid and other impurities in the upper layer were drained.

To remove methanol and water from the esterified oil a rotary evaporator was employed at 100°C under vacuum for 1 hour and 20 minutes.

To complete the process reaction an alkaline catalyzed process was employed by reacting the esterified oil with methanol at 6:1 molar ratio and 1% potassium hydroxide (KOH) at 80°C for 2 hours and a stirring speed of 400 r/min.

The final step to obtain a refined biodiesel oil was to leave the produced biodiesel in a separation funnel overnight, for the reaction to end. This process required 12 hours to finish reacting before the lower layer of impurities can be discarded.

2.3 WPPO fatty acid composition

The fatty acid for a double bond is unsaturated, so a single bond fatty acid, which is saturated, was tested using the FT-IR and confirmed by the GC-MS method. **Table 2** shows the GC-MS operating conditions while **Table 3** shows the FT-IR indicated compounds of pyrolysis biodiesel oil and their class of compound.

The biodiesel obtained was composed of more than 20 compounds of mixed proportion whose composition and GC-MS percentage areas spectrum are presented in **Table 4**. **Table 5** has a list of test equipment utilized in the experiment.

Considering percentage areas of the spectrum, the highest pick areas of the total chromatography were the following: heptadecane, n-octadecane, n-hexadecane, nonadecane, pentadecane, eicosane, tetradecane and tridecane. Eq. 1 shows the effect of linear velocity of the carrier gas in retention time which was used to determine the carrier gas linear velocity.

$$t_r = L \frac{(K + 1)}{\mu} \quad \# \quad (1)$$

Where.

t_r is the retention time.

L is the column height.

K is the retention factor (constant).

μ is the carrier gas linear velocity.

The components present in mixed WPPO range from carbon number C₁₀ to C₄₀. A large percentage of these components are made of aliphatic compounds as shown by the result the GC-MS spectrum result in **Table 4**.

Property	Specification
Carrier gas	Helium @ 23.8 psi
Linear velocity	44 cm/s@100°C
Flow rate	Air = 450 ml/min
	H ₂ = 40 ml/min
	He = 20 ml/min
Injector	Split injector, 50:1ratio, 0.3 µL injection volume
Temperature ramp 1	100°C zero minutes hold
Temperature ramp 2	10 °C/min to 250°C 5 minutes hold
Detector temperature	250°C
Column head pressure	23.8

Table 2.
 Showing GC–MS operating conditions during the experiment.

Frequency range (cm ⁻¹)	Group	Class compound
3750–3250	O-H stretching	Polymeric O-H, HO ₂ impurities
3150–2950	C-H stretching	Alkanes
1950–1830	C=O stretching	Ketones, aldehydes, carboxylic acid
1830–1725	C ≡ C stretching	alkenes
1725–1575	-NO ₂ stretching	Nitrogenous compounds
1575–1475	C-H bending	alkanes
1475–1375	C-O stretching	Primary/secondary alcohols
1325–1200	O-H bending	Esters, ethers, phenols
1175–1150	C-H bending	alkanes
1000–950	C ≡ C stretching	alkynes
900–875	—	Aromatic compounds

Table 3.
 FT-IR WPPO indicated compounds of pyrolysis biodiesel oil.

Composition	Chemical name	Percentage
C10	Aliphatic compounds	65
C10-C13	Doxosane	2.4
C13-C16	Isoparaffin	7.5
C16 - C20	1-hexadecene	3.1
C20 – C23	Eicosane	7.6
C23-C30	Docosane	15.4
C		81.5
H		11.3
O		7.2

Table 4.
 Elemental fatty acid composition of WPPO.

Property	Equipment	Standard
Kinematic viscosity	SVM 4000 (Anton Paar, UK)	ASTM D445
Flash point	NPM 550 (Norma lab, France)	ASTM D93
Oxidation stability	900 Rancimat (Metrohm, Switzerland)	ASTM D14112
CP/PP	NTE 500 (Norma lab, France)	ASTM D2500
Carbon residue	NMC 440 (Norma lab, France)	ASTM D4530
Total sulfur	5000 MULTI-EA (AJ Germany)	ASTM D5433
Calorific value	C 2500 basic calorimeter (IKA, UK)	ASTM D240
Density	SVM 3500 (Anton Paar, UK)	ASTM D1298

Table 5.
List of equipment used in the experiment.

2.4 WPPO properties analysis

In order to determine the physicochemical properties of the WPPO biodiesel Characterization tests were conducted based on the requirements and standards of ASTM D6751. Under this section, the following numbers were calculated using the fatty acid composition and empirical Equations [48, 49]. This included the saponification number, the cetane number and the iodine number. The saponification value is according to Eq. (2):

$$SN = \sum \frac{560 \times A_i}{MW_i} \# \quad (2)$$

The iodine value is according to Eq. (3):

$$IV = \sum \frac{254 \times D \times A_i}{MW_i} \# \quad (3)$$

The cetane index number is according to Eq. (4):

$$CN = 46.3 + \frac{5458}{SN} - (0.22 \times IV) \# \quad (4)$$

Where:

A_i is the weight percentage of each fatty acid component.

D is the number of double bonds in each fatty acid.

MW_i is the molecular weight.

To ensure proper mixing and blending of the various ratios during the experiment homogenous mixing equipment was used at speeds of 1800 r/min to 2000 r/min.

2.5 Engine testing and performance analysis

The engine test was conducted on a four-cylinder Iveco diesel dual fuel engine. To help in the analysis of the engine pressure, sensors and crankshaft position sensor and encoder were used. The aim of these two sensors was to provide the in-cylinder pressure in relation to the crankshaft position variation, using LabVIEW software. Combustion data was obtained, and graphs sketched.

The engine was coupled to a mechanical dynamometer with idling positions set at 500 r/min considered to be equivalent to 25% load, 1000 r/min for Mode 1

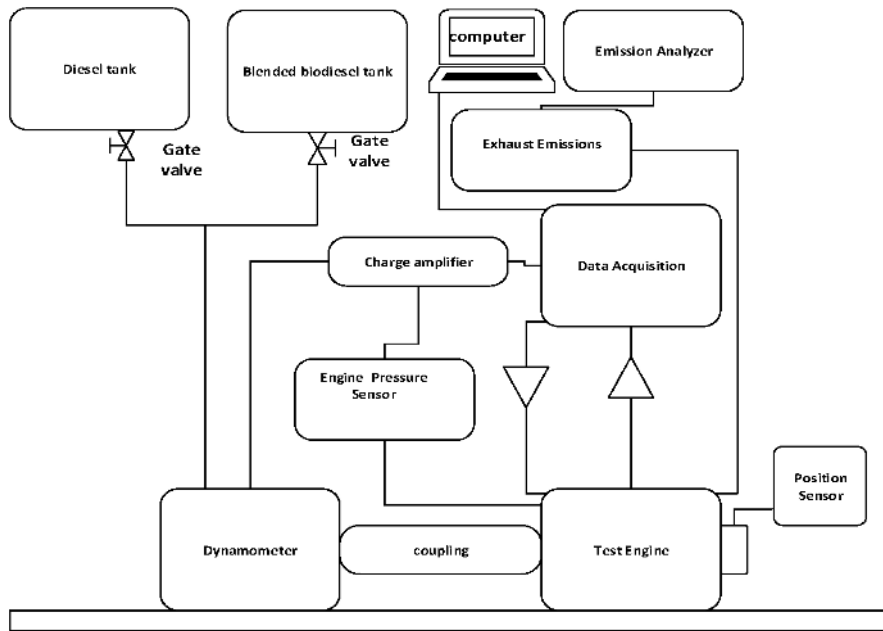


Figure 2.
 Schematic diagram of the engine testing and equipment.

Parameters	Position value
Ignition type	4 (Stroke)DICl
Number of cylinders	4 in-line
Cooling medium	Water
Manufacturer	Iveco
Revolutions per minute	2000
Brake power	43.40 kW@2000
Cylinder bore	104 mm
Piston stroke	115 mm
Compression ratio	17:1
Connecting-rod length	234
Engine capacity	2500 cc
Dynamometer make	234
Injection timing	12 bTDC
Maximum torque	206.9 Nm @1500
Injection pressure	250–272 Bar

Table 6.
 Experimental engine specifications.

equivalent to 50% engine load. For intermediate speeds two speeds are chosen as 1500 r/min and full load at 2000 r/min for Mode 2 as 75% and 100% engine load equivalents respectively. For engine load the dynamometer is fitted with a screw type loading device enabling each load to be synchronized with the intended engine speed targeted. **Figure 2** shows the schematic of the test engine and **Table 6** shows the engine specification.

3. Results and discussion

3.1 Brake specific fuel consumption (BSFC)

Fuel consumption as BSFC is a measure of fuel flow per unit time measured as a flow rate. The fuel thus measures how an engine utilizes supplied fuel to produce the intended work. While measuring BSFC lower values are preferred compared to higher values. The brake specific fuel consumption measures the efficiency of fuel by combustion of the fuel and air mixture, which does the actual work of crankshaft rotation. In other word, the BSFC is a ratio of the rate of fuel consumption in relation to the effective power produced by the engine. This means for every cycle of operation the BSFC tries to get an equal output with the corresponding increase in fuel supply to the engine (the engine is supplied volumetrically).

Figure 3 is a variation of BSFC with engine speed, and shows that as the speed increases, there is an equal increase in the fuel consumed by the test engine. The values obtained at full engine load for the blends of 95/WPPO5, 90/WPPO10, and 80/WPPO20, 70/WPPO30, 60/WPPO40 and PD were 0.4 kg/kW.h, 0.41 kg/kW.h, 0.42 kg/kW.h, 0.43 kg/kW.h and 0.35 kg/kW.h respectively. At high engine loads the conversion of heat energy to mechanical energy increased with increase in combustion temperature, leading to increased BSFC for the biodiesel. This increase was proportional to the difference in their heating values which is identical to the findings of [50]. Furthermore, the WPPO blends had high densities, therefore suffered high mass injection pressure, hence an increase in BSFC which is identical to studies by [51, 52]. WPPO blends compared well to conventional diesel fuel and sometimes other biodiesel blends with comparative differences in the heating values.

As the blend ratio increased there was a decrease in the BSFC across all the test fuels. However, the values for all WPPO blends increased compared to PD test fuel. This is due to the lower calorific values of the blends as the percentage of the blend ratio increased. In other words, by increasing the ratio of WPPO in the diesel test fuel the engine fuel consumption increased. This is identical to the studies of [53–55]. The closeness of the values and the packed graph reveal a close resemblance and identical BSFC characteristics of WPPO to PD properties. For example, **Figure 3** at Mode 1 (500 r/min (25% load) to 1000 r/min 50% engine load) blend 90/WPPO10 had a value of 0.48 kg/kW.h and 0.43 kg/kW.h compared to full engine speed Mode 2 2000 r/min

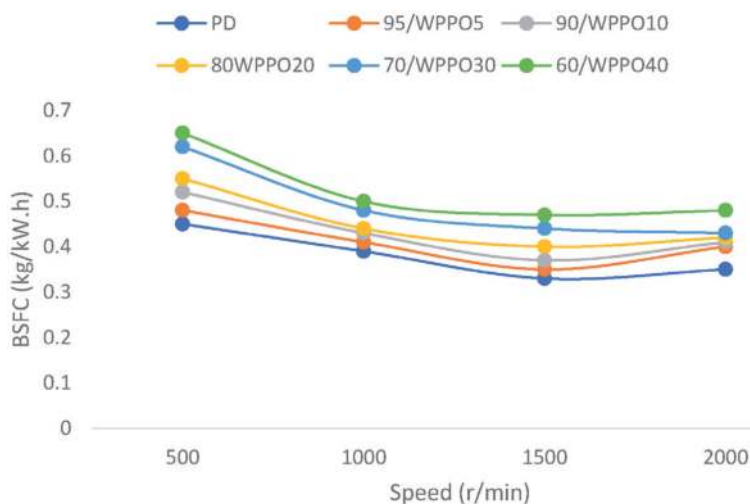


Figure 3. Brake specific fuel consumption versus speed.

100% load) with 0.37 kg/kW.h and 0.41 kg/kW.h. This value is higher than PD with 0.4 kg/kW.h at 1000 r/min 50% engine load and 0.35 kg/kW.h at full engine load.

3.2 Brake thermal efficiency (BTE)

The BTE measures the ratio of the engine brake power to the heat of combustion supplied by the fuel consumed by the engine. The brake thermal efficiency also determines how well the engine converts the heat energy into actual mechanical energy. The BTE is influenced by engine design, type of fuel used and the engine application [56]. High engine load seems to increase BTE as can be seen in intermediate loads of 1000 r/min 50% engine load to 1500 r/min 75% engine load. When operating at part load the gross thermal efficiency of any engine falls to 28%, which translates to a rating of 22% down, from a full load thermal efficiency at 39.1%. Modern on-road diesel engines provide a 42% BTE at full load but waste almost 28% of all fuel used through exhaust gases.

The BTE variations with engine load is shown in **Figure 4**. The graphs show that as the load increased there was an increase in the BTE across all the test fuel blends of WPPO and PD. The result of this experiment shows that the BTE increased as the load increased, explained by the reduction in the heat loss as the engine power (more fuel) increased with load.

At Mode 1 (1000 r/min, 50% engine load) the values for blends 95/WPPO5, 90/WPPO10, 80/WPPO20, 70/WPPO30, 60/WPPO40 and PD were 22%, 21%, 20%, 18%, 16.5% and 22.5% respectively. As the blend ratio and engine idling load increased there was an increase in BTE across the blends of WPPO, but with a decrease in the BTE within the blends. For example, at Mode 1 (500 r/min, 25% engine load), 95/WPPO5 had values of 14%, 22%, 26.5% and 25.7% compared to 80/WPPO20 with 12.5%, 20%, 22.5% and 23% respectively.

This decrease in BTE within the blends is due to the presence of aromatic compounds in waste pyrolysis plastic oil, which require a lot of energy to break [18]. Another critical factor that could be contributing to lower BTE among blends of WPPO compared to PD fuel is the higher combustion temperature characteristics observed in WPPO fuel blends leading to high heat transfer losses [57]. The main factors causing reduction in the BTE with use of blends is their lower heating values, low air to fuel mixing (poor atomization of blends during injection), high viscosity, high biodiesel density, or higher BSFC [58].

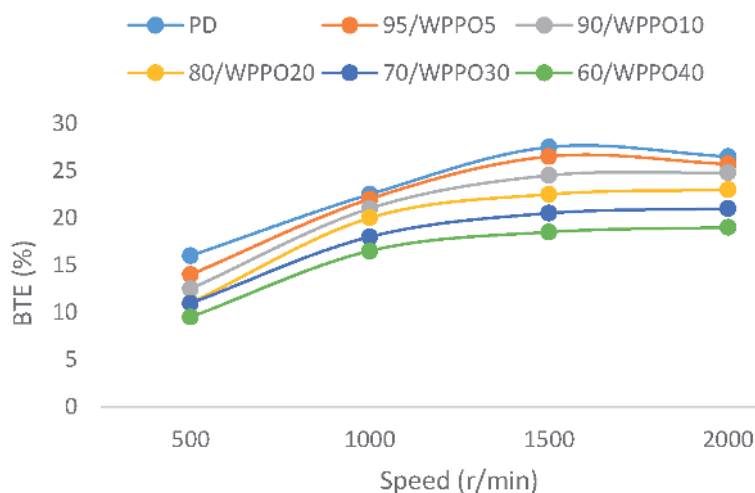


Figure 4.
Brake thermal efficiency versus speed.

The highest BTE value was 24.5% by blend 95/WPPO5 at 1500 r/min (Mode 2, 75% engine load) compared to any other blend of WPPO. **Figure 4** shows values of 24.8%, 23%, 21% and 19% for full speed 2000 r/min 100% engine load, Mode 2) respectively for blends 90/WPPO10, 80/WPPO20, 70/WPPO30, and 60/WPPO40. However, blend 60/WPPO40/E25 reported the lowest values compared to the other blends. At 500 r/min (Mode 1, 25% engine load), the BTE value was 9.5% compared to 19% at full load 2000 r/min, Mode 2). These two are the lowest values of BTE for all the blends tested, as shown in **Figure 4**.

3.3 Carbon monoxide (CO)

Figure 5 is a variation of CO with two engine load modes (Mode 1, and Mode 2) with speed range of 500 r/min 25% engine load to 2000 r/min 100% engine load. The graph reveals that as the engine speed, load and the blend ratio increased, CO emissions reduced up to engine speeds of 1500 r/min (Mode 2, 75% of engine load). This was for PD and all blends 95/WPPO5, 90/WPPO10, 80/WPPO20, 70/WPPO30, and 60/WPPO40; the values were 270 ppm, 285 ppm, 315 ppm, 345 ppm, 370 ppm, 385 ppm respectively. The highest value of CO emission reported was 485 ppm for blend 60/WPPO40 and the lowest value reported was for blend 95/WPPO5 at 388 ppm.

Another observation is that as the engine was approaching full load (Mode 2, 2000 r/min), all the test fuels showed increased CO emissions with blends 95/WPPO5 and 90/WPPO10 reporting the lowest emissions value of 388 ppm and 435 ppm among the test blends across the entire engine load Modes 1 and 2 conditions. However, as the load increased from Mode 1 25% engine load speed of 500 r/min to Mode 2 (75% engine load) the values reported were 320 ppm and 335 ppm respectively.

There are a number of factors, which explain the low CO emissions as the engine load and speed is increasing. The reason the blends show decreasing and increasing trends for Modes 1 and 2 respectively is due to high viscosity in WPPO. Viscosity affects the spray pattern resulting in poor fuel mixing therefore incomplete combustion and increased carbon monoxide emissions [59]. This phenomenon is linked to the increased engine load and the short ignition delay, hence increasing CO emissions. Additionally, the decrease in CO emissions could be due to the conversion of CO to CO₂ taking up this reaction from the high oxygen content of biodiesel [60].

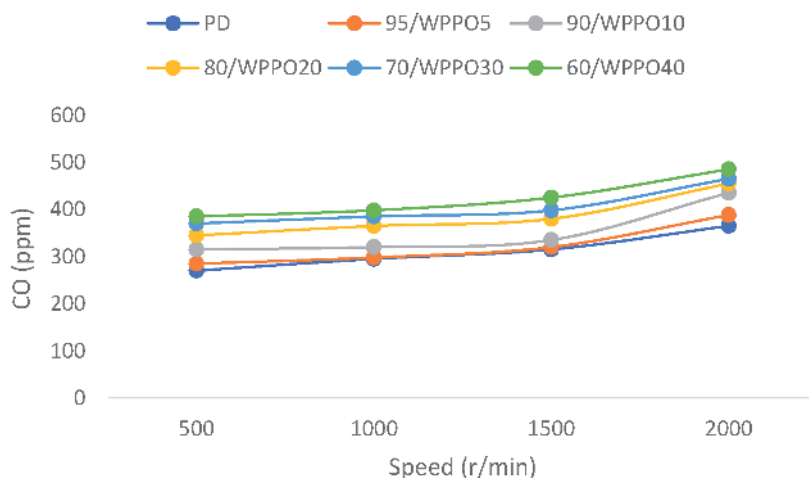


Figure 5.
Carbon monoxide versus speed.

3.4 Unburnt hydrocarbons (UHC)

UHC exhaust emissions are due to poor atomization after injection, over leaning zones and wall flame quenching [61, 62]. **Figure 6** is a variation of UHC emission with engine load. As the engine load and engine speed increased, the UHC emissions increased too. However, the increase was more significant as the engine load was in intermediate loads Mode 1 and Mode 2, 1000 r/min to 1500 r/min full load (50–75%). For example, at Mode 1, (1000 r/min, 50% engine load), the blend values were 23 ppm, 24 ppm, 26 ppm, 28 ppm, and 30 ppm respectively compared to full load Mode 2 2000 r/min) with 13 ppm, 15 ppm, 16 ppm, 18 ppm, and 26 ppm for blends 95/WPPO5, 90/WPPO10, 80/WPPO20, 70/WPPO30, and 60/WPPO40 respectively.

The blends 95/WPPO5 and 90/WPPO10 produced lower UHC emissions compared to the other test blends. The trends in **Figure 6** show high emission values for the blends compared to the PD test fuel values. However, the general trend in **Figure 6** shows that increased blend ratio significantly reduced UHC emissions across all the test fuels irrespective of the engine Mode. This reduction is due to the high oxygen of WPPO which has an oxygen content of 7.83 as shown in **Table 6** and in Section 3 of the results and discussion.

There are two main causes of increased hydrocarbon emissions, due to hydrogen radicals in diesel-WPPO blends and the presence of higher aromatic compounds [63]. Another contribution is caused by high density, low viscosity and low cetane of WPPO blends resulting in poor spray characteristics, leading to wall impingement, thus high UHC emissions. High blend ratio has also been identified as a factor that influences formation of UHC emissions using WPPO and has been reported by a number of researchers such as [64–66]. Hence the conclusion that high engine loads increases the values of UHC emissions proportionately to petroleum diesel. Increased UHC emissions can also be attributed to engine operating environment especially if the temperature range of 400–600°C exists in the combustion chamber. This is due to diesel exhaust pipe reaction, which either lowers or increases the concentration of UHC [67, 68].

3.5 Oxides of nitrogen (NO_x)

It is an established fact that NO_x emission are a function of in-cylinder temperature and atmospheric nitrogen, which is at 78% during intake. NO_x emissions are also a

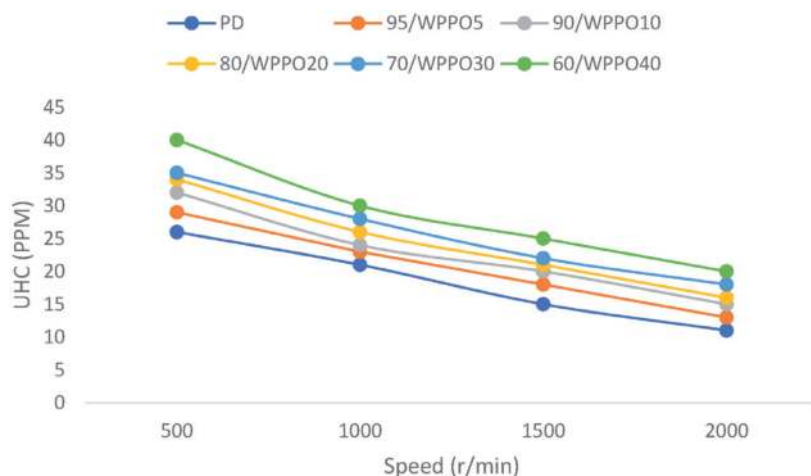


Figure 6.
Unburnt hydrocarbons versus speed.

function of three main mechanisms in the combustion theory [61, 69]. **Figure 7** is a variation of engine idling load with NO_x emissions. The figure shows that as the engine idling load was increased there was an increase in the NO_x emissions irrespective of fuel blend ratio. The values of NO_x emissions for the blends 95/WPPO5, 90/WPPO10, and 80/WPPO20 reported higher values at (Mode 2, 75% load) compared to Mode 1. For example, at 1500 the values of the blends were 335 ppm, 358 ppm, and 475 ppm, compared to PD fuel at 300 ppm.

Table 7 is showing different test fuel properties, units of measurement and testing standards used in this experiment. Blends 70/WPPO30 and 60/WPPO40 had the highest NO_x emissions compared to the other blends of 95/WPPO5, 90/WPPO10, and 80/WPPO20 across all the engine load conditions tested.

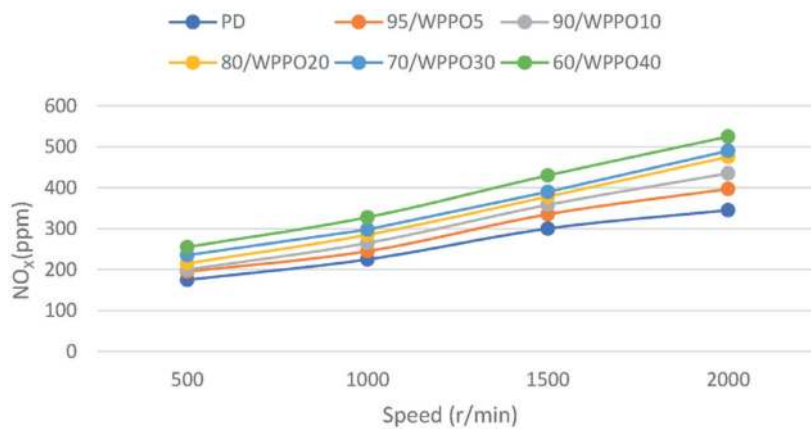


Figure 7.
Oxides of nitrogen emissions versus different engine speeds.

Property	Unit	PD	WPPO	Standard
Appearance	—	Clear/brown	Clear/amber	Visual
Density @ 20 °C	kg/M ³	838.8	788.9	ASTM D1298
Kinematic Visc @ 40 °C	mm ² /s	2.32	2.17	ASTM D445
Flash point	°C	56.0	20.0	ASTM D93
Cetane index	—	46	65 ^a	ASTM D4737
Hydrogen	%	12.38	11.77	ASTM D7171
Cu corrosion	3 hrs @ 100°C	—	1B	ASTM D130
Carbon	%	74.99	79.60	ASTM D7662
Oxygen	%	12.45	7.83	ASTM D5622
Sulfur content	%	< 0.0124	0.15	ASTM D4294
IBP temperature	°C	160	119	ASTM D86
FBP temperature	°C	353.5	353.5	ASTM D86
Recovery	%	—	98	—
Residue and loss	%	—	2.0	—
Gross calorific value	MJ/kg	44.84	42.15 ^b	ASTM D4868

a and b are calculated values.

Table 7.
Test fuel biodiesel properties, units of measurement, testing standard methods and the values for PD compared to WPPO.

At 500 r/min 25% engine load (Mode 1), the two blends (70/WPPO30, 60/WPPO40) had values of 235 ppm and 255 ppm respectively. However, at full speed (2000 r/min, 100% engine load (Mode 2) the NO_x emissions for the two blends increased to 490 ppm and 525 ppm respectively compared to blends 95/WPPO5 for the same speed and engine load (500 r/min, Mode 1) at 175 ppm and at full load (2000 r/min, Mode 2) at 345 ppm.

As the blend ratio in **Figure 7** increased there was a direct increase in emissions of NO_x across all the blended fuels. However, blend 95/WPPO5 and 90/WPPO10 reported the lowest values of NO_x emissions (175 ppm and 195 ppm) compared to all the other tested blends experimented. The formation of NO_x in biodiesel fuel combustion strongly depends on the combustion temperatures and the oxygen concentration in the combustion zone. The high blend ratios of 80/WPPO20, 70/WPPO30, and 60/WPPO40 showed a shortened combustion process. Thus, a poor cooling effect and failure to decrease peak combustion temperatures leads to increased NO_x. WPPO blends emitted higher NO_x due to the higher cetane index compared to diesel fuel. High cetane index number fuels have a shorter ignition delay which means longer residence time at elevated chamber temperatures, hence higher NO_x compared to PD.

The increased NO_x emissions are a result of the presence of increased cetane index [70, 71] and other contaminants from the WPPO biodiesel impurities. Additionally, this could be due to the generation of radicals of hydrocarbons through molecular unsaturation in the blends, this being identical to the findings of [72, 73]. The final factor is due to increased chamber temperature which improves combustion but increases NO_x emissions, linked to the high oxygen content and the air fuel ratio factors [49].

4. WPPO combustion analysis

Due to the high cetane index of WPPO biodiesel the combustion process starts early compared to PD, hence a higher release rate than PD combustion. This leads to a higher cylinder peak pressure for WPPO biodiesel fuel compared to PD. Depicted in **Figure 8**, is a comparison of s WPPO blends with PD in Mode 1 25% engine load at speeds 500 r/min to 1000 r/min. Under this condition, WPPO blends in Mode 1

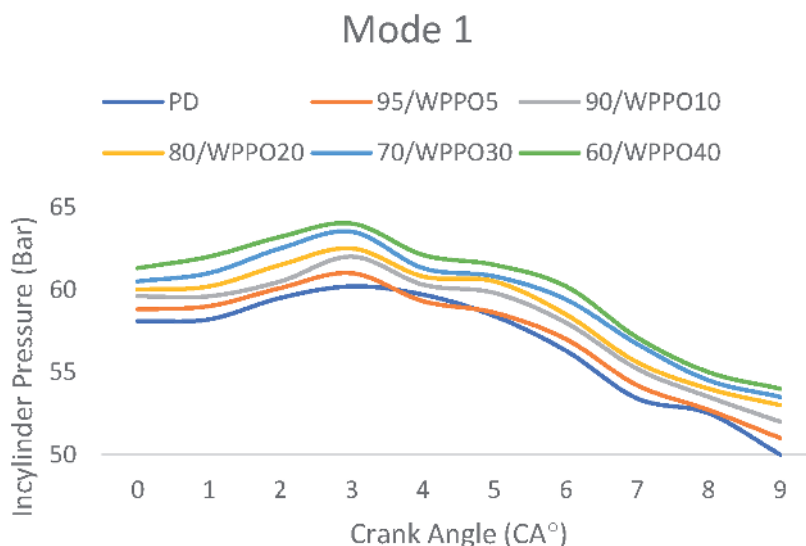
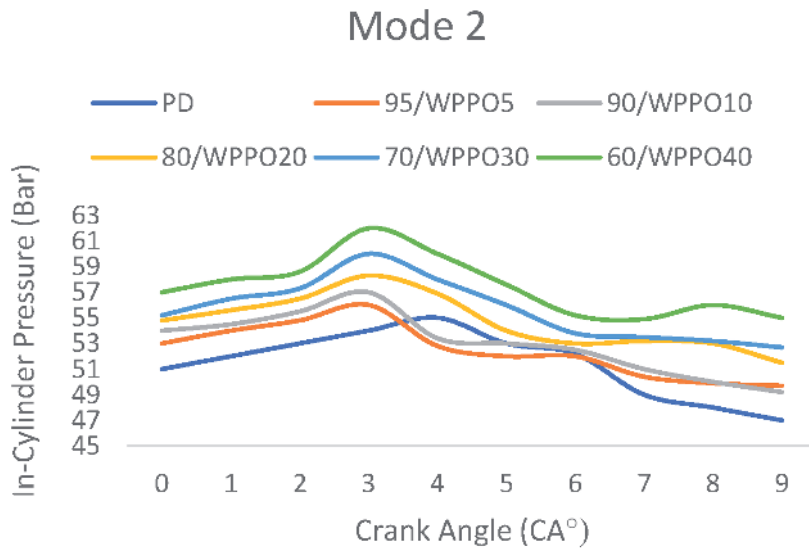


Figure 8. In-cylinder pressure vs. crank angle variation compared to diesel and WPPO.

**Figure 9.**

In-cylinder pressure vs. crank angle variation compared to diesel and WPPO in mode 2.

exhibited higher peak cylinder pressure compared to PD, which is evident as the blend ratio increased as in **Figure 8**.

Compared to when the engine is running at high speed (high load), low speeds and low load residual gas temperatures and engine wall temperatures are low [69]. In other words, injection pressure and fuel temperature are low hence increased delay. This is the explanation why diesel in the combustion analysis starts after 3° CA compared to WPPO biodiesel blends. This causes diesel fuel to reach peak cylinder pressure after top dead center (TDC) in the power stroke. On the other hand, biodiesel blends reach peak cylinder pressure early, i.e., before TDC in the power stroke. For example, in **Figure 9** Mode 2 speed, the value for peak cylinder pressure for PD fuel is 55 bar compared to 56 bar for WPPO blend 95/WPPO5. This is due to enhanced combustion resulting from rapid combustion of the biodiesel blends at the pre-mixed phase. Of all the test fuels PD had the lowest peak cylinder pressure which occurs slightly after TDC [74].

5. Conclusion

- In the discussions in Section 3 under BSFC it was observed that, at high engine loads the conversion of heat energy to mechanical energy increased with increase in combustion temperature, leading to increased BSFC for the bio-diesel. The increase was found to be proportional to the heating values of the different test fuels.
- Due to high densities exhibited by most biodiesel blends it was observed that blends suffer from high mass injection pressures which is in return increases the BSFCs of blends.
- As the percentage of the blend ratio increased there was a proportionate increase in engine fuel consumption due to lower calorific values of the blends. However, the values for all WPPO blends increased compared to PD test fuel.
- The Brake thermal efficiency of diesel engines was observed to be influenced by engine design, type of fuel used and the engine application. High engine

load and speeds seems to increase BTE as can be seen in intermediate loads of 1000 r/min 50% engine load to 1500 r/min 75% engine load.

- Result obtained during this experiment show that the BTE increased as the load increased. This is explained by the reduction in the heat loss as the engine power (more fuel) increased with load.
- As the blend ratio and engine load and speed increased there was an increase in BTE across the blends of WPPO, but with a decrease in the BTE within the blends. This was attributed to the presence of aromatic compounds in waste pyrolysis plastic oil, which require a lot of energy to break.
- During experimentation it was observed that as the engine was approaching full load (Mode 2, 2000 r/min), all the test fuels showed increased CO emissions.
- As the engine load and engine speed increased, the UHC emissions increased too. However, the general trend in **Figure 6** shows that increased blend ratio significantly reduced UHC emissions across all the test fuels irrespective of the engine Mode.
- As the engine load and speed increased there was an increase in the NO_x emissions irrespective of fuel blend ratio.
- As the blend ratio increased there was a direct increase in emissions of NO_x across all the blended fuels.

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