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The Effects of High Biodiesel Blend Ratios of Waste Plastic Pyrolysis Oil in ompression Ignition Engine Load

Semakula Maroa[1] And Freddie Inambao[2]

[1]*Researcher and Lecturer, University of Eastern Africa Baraton, School of Science and Technology, Technology Department, 2500-30100, Eldoret, Kenya.*

[2]*Professor, College of Agriculture Science and Engineering, Department of Mechanical Engineering, Green Energy Group, University of KwaZulu-Natal, Durban 4001, South Africa*

***Abstract*:**

This work had three main objectives, to use waste plastic pyrolysis oil (WPPO) blends to determine the effects of high blend ratios on idling speed load in a diesel engine, the impact of high blend ratios of WPPO at low and intermediate engine conditions on brake specific fuel consumption (BSFC), also known as high idling condition. Lastly, the study aimed to find the effect of using high blend ratios of WPPO on engine performance and emission characteristics at high idling. The Findings show that at all engine loads (from idling to full load) the emissions of carbon monoxide (CO), unburnt hydrocarbon (UHC) and carbon dioxide (CO_2) were low compared to conventional diesel (PD). However, the emissions of NO_X were higher in all the high blend ratios compared to PD. The brake specific fuel consumption (BSFC) for the high ratio blends dropped while the brake thermal efficiency (BTE) increased with load for all high blend ratios until intermediate load, showing a decreasing trend in the values recorded. Notable results showed that WPPO high blend ratios had higher viscosity compared to PD. For example, CO emissions for blend ratio 80/WPPO20 at all engine idling, intermediate and high-speed modes were 345ppm, 365 ppm, 380 ppm, and 455 ppm while PD emissions were 270 ppm, 295 ppm, 315 ppm and 365 ppm respectively. The values for UHC for blend ratio 80/WPPO20 at all engine experimental modes were 34ppm, 26ppm, 21ppm, and 16ppm compared to PD fuel with 20 ppm, 25 ppm, 30 ppm, and 40 ppm respectively. The NO_X emissions for PD fuel at all engine experimental modes were 175 ppm, 225 ppm, 300 ppm and 375 ppm compared to blend 80/WPPO20 at 215 ppm, 285 ppm, 378 ppm, and 475 ppm. The BSFC values for blend 80/WPPO5 at all engine experimental modes were 0.48 kg/kW.h, 0.41 kg/kW.h, 0.35 kg/kW.h and 0.4 kg/kW.h respectively, 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*:** Blend ratio, Engine loads, Emissions, intermediate load, Higher viscosity, engine experimental modes

INTRODUCTION

Alternative fuel energy Development began in the 1900s with German engineer Rudolf Diesel who invented the diesel engine initially using vegetable oil. However, due to the discovery of petroleum-based fuels at the time, the focus moved to fossil fuels thus disadvantaging bio-oil development (Palash et al., 2013). Many contemporary researchers such as (Inambao, 2018; Kim et al., 2022; Praveenkumar, Velusamy, & Balamoorthy, 2022; Sadaf et al., 2018) have focused on the development of alternative fuels to petro-diesel (PD). Most of this research is heavily leaning towards creating biodiesel-based fuels as a solution to replace fossil fuels. These developments besides creating renewable and alternative fuels, add to the bouquet of green fuels. It is important to note that Fossil fuels are non-renewable and deplete rapidly, hence creating the need for large-scale research for alternative renewable fuels. With the increase in global warming, alternative fuels must be economically and socially feasible, besides being environmentally friendly and sustainable in meeting the existing large energy demand present globally (Kavitha, Beemkumar, & Rajasekar, 2019; Rahman et al., 2014).

Detrimental environmental impacts of Fossil fuels cannot be gainsaid when released into the atmosphere due to the combustion and extraction activities of fossil fuels. Projections indicate that if no measures are put in place the use of fossil fuels will raise emission levels by 39 % by 2030(Che Hamzah, Khairuddin, Siddique, & Hassan, 2020; Singh & Singh, 2012; Zietsman et al., 2018). Besides environmental concerns and degradation, the demand and supply of fossil fuels in the international market is erratic prices hence promoting inflation on other commodities (Melichar & Atems, 2019). Globally, governments and different non-governmental organizations have taken many measures to combat environmental pollution. For example, European Union countries have imposed taxes based on social contribution from the transportation industry as a function of gross domestic product (Eurostatistics, 2018; Wolde-Rufael & Mulat-Weldemeskel, 2023). This is reflected in Figure 1 shows.

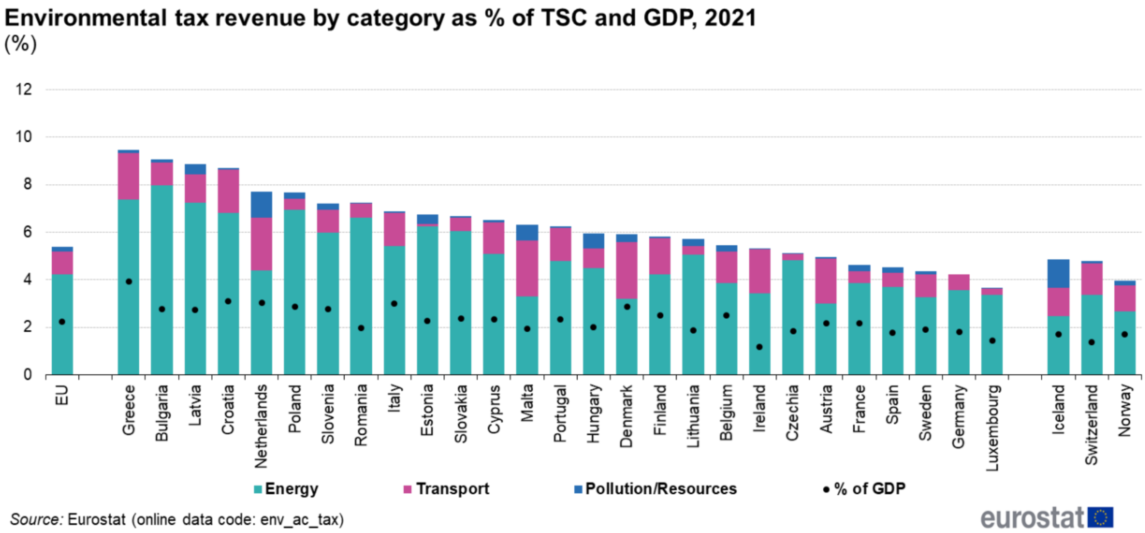

Figure 1. Environmental taxes as % of GDP and as % of total taxes and social contributions (Eurostatistics, 2021)

Researchers from the mainstream have evaluated engine performance using different feedstock and biodiesel blends to determine the efficacy of biodiesel (Devarajan et al., 2022; Mahmudul et al., 2017; Mourad, Mahmoud, & NourEldeen, 2021; Selvan et al., 2022). Nonetheless, only a limited number have been able to investigate the influence of load using plastic waste oil blends of biodiesel such as (Kaewbuddee et al., 2020; Mustayen et al., 2023; Venkatesan, Sivamani, Bhutoria, & Vora, 2018, 2019). In the literature reviewed published work has been concentrated on areas of performance and emission characteristics but little attention to low load and intermediate load compared to engine full load but no high blend ratios (Kavitha et al., 2019; Solomon et al., 2022; Uyumaz, 2018). However, in the transport industry, all low-load and intermediate engine idling speeds are considered as high idling, and mostly this is the cause of increased emissions from trucks and light-duty vehicles.

High idling which in practice is considered low engine loads increases NO_X emissions on roads compared to high-speed road driving by a factor of 1.5 (Calcagno III, 2005; Maroa & Inambao, 2021). In other words, increasing low load increases NO_X emissions (Chacko, 2020; McCaffery et al., 2020; Roy, Calder, Wang, Mangad, & Diniz, 2016). On the other hand, during idling, which is considered low load, the fuel consumption as well as engine wear and maintenance increase. For example, in trucks, the average fuel consumption at idle is 0.8 g/hr to 1.5 g/hr. The determining factors are based on the engine capacity, ambient temperature and operating systems loads such as HVAC or vehicle electrical loads. However, when the NOx emissions are compared to driving cycle emissions of UHC the quantities are 1-5 times more for the latter.

During low engine load, studies have shown that other emissions such as CO rise to 295 g/hr (Deng et al., 2020; Maroa & Inambao, 2021; Sharma, Kumar, Dhyani, Ravisekhar, & Ravinder, 2019; Wang et al., 2021). In the literature reviewed during the driving cycles, carbon emissions are estimated at 45 % to 75 %, while UHC emissions during idling and low load can reach 86.4 g/hr (Dev, 2021; Zhou et al., 2018). Typically, most diesel engines spend a substantial amount of time in idling mode. This can be seen in either traffic stops, checkpoints or during fuelling in stations or depots. The time spent with trucks idling varies considerably but mainly this falls on the preference of individual drivers. However, for long haulage trucks, the following are given as reasons this phenomenon is reported as climate control, loading and offloading transport cargo, service or maintenance stops (Kumar & Anbanandam, 2022; Yeow & Cheah, 2021). The other reason in the literature surveyed why trucks idle for long is the use of the engines to heat and air-condition cabs besides powering amenities in the cabs during road operations and traveling (Huang et al., 2018; Zietsman et al., 2018).

Biodiesel oil is known to contain physicochemical characteristics of functional PD properties (Islam, Primandari, & Yaakob, 2018; Nouni et al., 2021; Syafiuddin, Chong, Yuniarto, & Hadibarata, 2020). In literature surveyed and reported Research biodiesel fuels have been shown to contain many advantages over PD. These advantages include biodegradability, non-flammability, renewability, non-explosiveness, non-toxic and are considered environmentally friendly (Al-Esawi, Al Qubeissi, & Kolodnytska, 2019; Mathew et al., 2021). These qualities indicate and support biodiesel fuels as a good alternative or option substitute for fossil fuels. Biodiesel fuels have a variety of feedstocks and sources such as used vegetable oil, waste plastics, waste biomass, waste animal fats (tallow) and more recently microalgae. These feedstocks can be processed into biodiesel fuel for propulsion and energy production (Ramos, Dias, Puna, Gomes, & Bordado, 2019). Biodiesel fuels have a technical advantage, In other words, biodiesel fuels can be utilized as fuel with or without engine modification which has been identified by several researchers (Hazrat et al., 2021; Jeyakumar & Narayanasamy, 2021; Longanesi, Pereira, Johnston, & Chuck, 2022).

In the literature reviewed diesel engine performance characteristics are affected by the use of biodiesel and biodiesel blends. As a result, Poor biodiesel fuel quality results in deposits and clogging in internal combustion engines(Abed, Gad, El Morsi, Sayed, & Elyazeed, 2019; Semakula Maroa & Freddie Inambao, 2019). Besides the above-mentioned issues, the use of biodiesel results in corrosion, and excessive engine wear leading to premature engine failure (Atmanli & Yilmaz, 2020). 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 (Li, Huang, Chen, & Tang, 2024; Patel, Hwang, Agarwal, & Bae, 2019). Additionally, the use of biodiesel fuel in internal combustion engines causes dilution of lubrication oil hence high crank-case oil levels followed by loss of engine oil pressure and increased engine bearing wear (Taylor, 2021). 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 main objective of this study was to use waste plastic pyrolysis oil (WPPO) blends to determine the effects of high blend ratios on idling speed load- in a diesel engine. secondly to study the effect of brake specific fuel consumption (BSFC) of WPPO at low and intermediate engine conditions, also known as high idling conditions using high blend ratios. The third objective was to find the effect of engine load at high idling on engine performance and emission characteristics using high blend ratios of WPPO as an alternative fuel.

Methodology and Materials

2.1 Crude WPPO Oil Properties

The selection and motivation of WPPO for this study was based on the advantage of turning waste into energy hence reducing the environmental impact of waste plastic. Secondly, the reason for the use of waste plastic oil is its sustainability as it is readily available in municipal solid waste management sites. The plastics for this experiment were collected from various holding facilities within the Durban metropolitan center 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(S Maroa & F Inambao, 2019). The WPPO testing and measurements were conducted at Intertek, a private laboratory in Durban and the results are shown in Table 1.

Table. 1. Properties of diesel and WPPO before processing into biodiesel properties

	Unit	PD	WPPO
Density @ 20 ℃	Kg/M^3	845	825
K. Viscosity @ 40 ℃	mm^2/s	3.04	2.538
Cetane number	-	55	-
Flash point	℃	50	43
Fire point	℃	56	45
Carbon residue	%	22	0.015
Sulfur	%	<0.028	0.248
Gross calories	MJ/kg	46.50	43.32

2.2 WPPO Biodiesel Processing

The processing of WPPO biodiesel took a two-step process due to the high acid value of this oil compared to petroleum diesel. Thus, an acid-catalyzed process maintained the molar ratio at 12: (50% v. v). During preparations, 1 % of H_2SO_4 was added to the preheated oil at 70 ℃ for 3.5 hrs with a stirring speed of 400 r/min in a reactor capacity of 5 litres.

The excess alcohol, sulphuric acid and other impurities in the upper layer were drained using a separating funnel and the final products were obtained. The products were put into an esterified oil rotary evaporator at 100 ℃ under vacuum for 1 hour and 20 minutes to separate water and methanol.

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 ℃ for 2 hours with a stirring speed of 400 r/min.

In order to obtain a refined biodiesel oil, the final step required 12 hours to finish the reaction process. This was achieved by leaving the produced biodiesel in a separation funnel overnight, for the reaction to end before the lower layer of impurities could be discarded.

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

Property	Specification
Carrier gas	Helium @ 23.8 psi
Linear velocity	44 cm/s@100℃
Flow rate	Air = 450ml/min
	H_2 = 40 ml/min
	He = 20 ml/min
Injector	Split injector, 50:1ratio, 0.3 µL injection volume
Temperature ramp 1	100 ℃ zero minutes hold
Temperature ramp 2	10 ℃/min to 250 ℃ 5 minutes hold

Detector temperature	250 ℃
Column head pressure	23.8

WPPO Fatty Acid Composition

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

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

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

The biodiesel oil obtained is composed of more than 20 compounds of mixed proportion. Table 4 has a list of test equipment utilized in the experiment, while Table 5 shows the Elemental fatty acid composition of WPPO.

Table. 4. List of equipment used in the experiment

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

The spectrum percentage areas show the highest pick areas of the total chromatography were the following: heptadecane, n-octadecane, n-hexadecane, nonadecane, pentadecane, eicosane, tetradecane and tridecane. The effects of linear velocity of the carrier gas in retention time which was used to determine the carrier gas linear velocity is shown in Equation 1.

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

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 ranged from carbon number C_{10} to C_{40} in mixed WPPO. The result indicates that a large percentage of these components are of aliphatic compounds as shown in Table 5 of the elemental fatty acid composition of WPPO obtained by GC-MS spectrum result.

Table. 5. Elemental fatty acid composition of WPPO

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

2.4 WPPO Properties Analysis

Determination of the physicochemical properties of the WPPO biodiesel Characterization tests was based on the requirements and standards of ASTM D6751. Under this requirement, 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 calculation of the iodine value is according to Eq (3):

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

The calculation of 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 various blend ratios, the homogenous mixing equipment speeds of 1800 r/min to 2000 r/min were used during the experiment.

2.5 Engine Testing and Performance Analysis

To conduct engine tests a four-cylinder Iveco diesel dual-fuel engine was used. For the analysis of the engine pressure, sensors and crankshaft position sensor and encoder were used. The in-cylinder pressure in relation to the crankshaft position variation came via the two sensors and their data collection using LabVIEW software, graphs were sketched and combustion data was obtained for analysis.

On the other hand, the engine was coupled to a mechanical dynamometer and the idling positions were set at 500 r/min which is equivalent to 25% load, and 1000 r/min equivalent to 50% engine load respectively for Mode 1. However, for intermediate speeds, two speeds were chosen at 1500 r/min and full load at 2000 r/min for Mode 2 as 75% and 100% engine load equivalents respectively. The engine dynamometer was fitted with a screw-type loading device enabling synchronized loading with the intended targeted engine speed. Figure 2 shows the schematic of the test engine, Table 6 shows the engine specification and Table 7 shows different test fuel properties, units of measurement and testing standards used in this experiment.

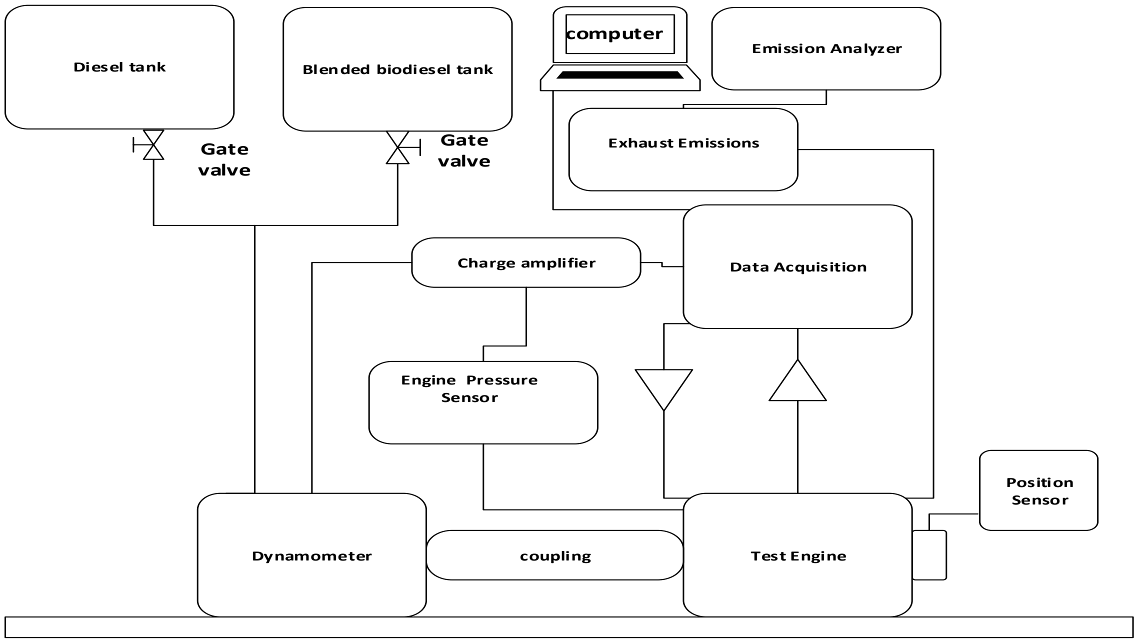

Figure 2. Schematic diagram of the engine testing and equipment ([50 Maroa et al 2021 assessing)

Table 6. Test engine technical specifications

Parameters	Position value
Ignition type	4 (Stroke)DICI
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	2500cc
Dynamometer make	234
Injection timing	12° BTDC
Maximum torque	206.9 Nm @1500
Injection pressure	250-272 Bar

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

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	3hrs @ 100 °C	-	1B	ASTM D130
Carbon	%	74.99	79.60	ASTM D7662
Oxygen	%	12.45	7.83	ASTM D5622
Sulphur 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

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 words, the BSFC is a ratio of the rate of fuel consumption with 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. From the figure as the speed increases, there is an equal increase in the fuel consumed by the test engine across all blend ratios. The values obtained at full engine load for the blends of, and 80/WPPO20, 70/WPPO30, 60/WPPO40 and PD were 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 (Lapuerta, Armas, Hernández, & Tsolakis, 2010). Additionally, as the load increased the oxygen content in biodiesel helped improve combustion in the cylinder thus compensating for the low calorific value which is consistent with the studies of (Al-Dawody & Bhatti, 2013; Çelik & Özgören, 2017). Furthermore, due the high densities characteristic of WPPO, the engine suffered high mass injection pressure, hence an increase in BSFC which is identical to studies by (Hira, Das, & Thakur, 2020; Tüccar, Tosun, Özgür, & Aydın, 2014; Zhang et al., 2021). WPPO blends compared well to conventional diesel fuel and other biodiesel blends with comparative differences in the heating values.

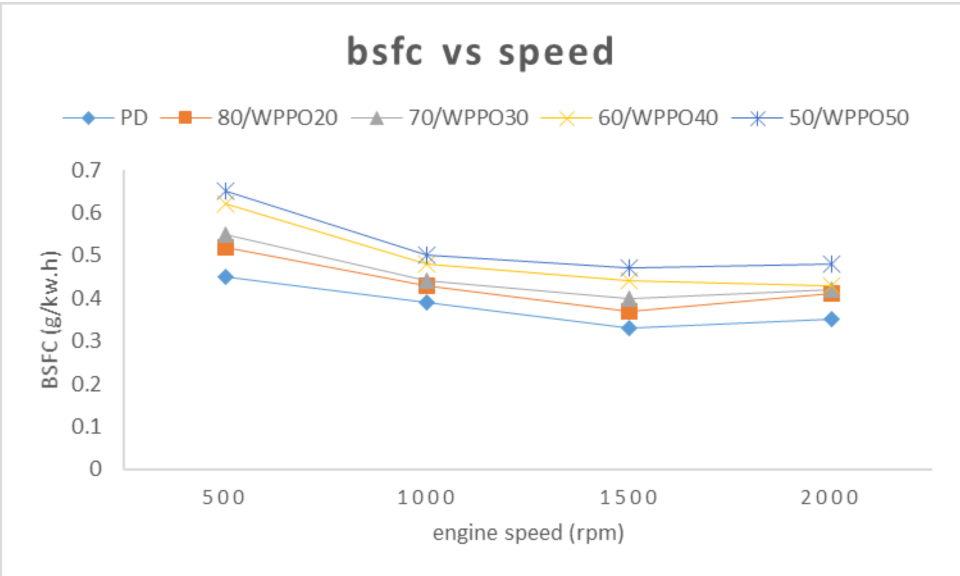

Figure 3. Brake specific fuel consumption versus speed

Increased blend ratios showed a decrease in the BSFC across all the test fuels 80/WPPO20, 70/WPPO30, 60/WPPO40, and 50/WPPO50 respectively. 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, increasing the ratio of WPPO and diesel blends increased fuel consumption. This is identical to the studies of (Kaisan, Anafi, Nuszkowski, Kulla, & Umaru, 2020). 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% engine load) to 1000 r/min (50 % engine load) blend 80/WPPO20 had a value of 0.52 kg/kW.h and 0.43 kg/kW.h compared to full engine speed Mode 2 @ 2000 r/min 100% load) with 0.37 kg/kW.h and 0.41 kg/kW.h respectively. 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 engine brake power is due to the ratio of heat of combustion supplied by the fuel consumed by the engine is called The BTE. The brake thermal efficiency additionally determines how efficiently an internal combustion engine converts the heat energy into actual mechanical energy able to do actual work. The BTE is influenced by engine design, fuel type and the type of application used for the engine(Ramalingam & Rajendran, 2019) . High engine load increases BTE at intermediate loads of 1000 r/min (50% engine load) and high loads of 150 r/min (75% engine load). Research has shown that operating any engine at part load results in 28 %, decrease in the gross thermal efficiency translating to a rating of 22 % down, compared to full load thermal efficiency at 39.1 %. Modern diesel engines' on-road tests provide a 42% BTE at full load but waste almost 28% of all fuel used through exhaust gases (Ramalingam & Rajendran, 2019).

The BTE variations with engine load are shown in Figure 4 below. From the graphs, as the load increased there was an increase in the BTE across all the test fuel blends of WPPO and PD. The result from the graph shows that the BTE increased with increased load, which is explained by the reduction in the heat loss as the engine consumption (power-more fuel) increased with load which is identical to the study by (Bisoi, Nayak, Sahu, & Mishra, 2017).

At Mode 1 (1000 r/min, 50 % engine load) the values for blends, 80/WPPO20, 70/WPPO30, 60/WPPO40, 50/WPPO50 and PD were 22.5 %, 21 %, 20 %, 18 %, and 16.5 % 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), blend 80/WPPO20 had values of 12.5 %, 21 %, 24.5 % and 24.8 % compared to 60/WPPO40 with 10.5 %, 18 %, 20.5 % and 21 % respectively.

In the literature surveyed, decreased BTE within the blends of WPPO is due to the presence of aromatic compounds in waste pyrolysis plastic oil. Their presence requires a lot of energy to break and combust them (Venkatesan et al., 2018). Another critical contributing factor leading to lower BTE among blends of WPPO compared to PD fuel is their higher combustion temperature characteristics observed in all WPPO fuel blends hence high heat transfer losses (Kalargaris, Tian, & Gu, 2017). Other contributing causes of reduction in the BTE with the use of blends of WPPO are their lower heating values, low air-to-fuel mixing (poor atomization of blends during injection), high viscosity, high biodiesel density, or higher BSFC (Uddin, Azad, Alam, & Ahamed, 2015).

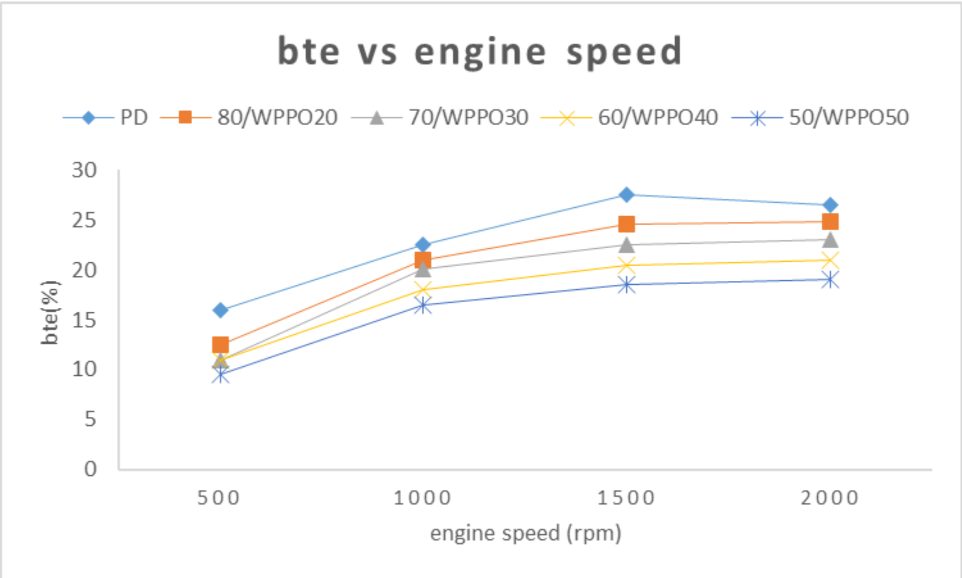

Figure 4. Brake thermal efficiency versus speed

In Figure 4, The highest BTE value was 24.8 % by blending 80/WPPO20 at 2000 r/min (Mode 2, 100 % 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 80/WPPO20, 70/WPPO30, 60/WPPO40, and 50/WPPO50. However, blend 50/WPPO50 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)

Incomplete combustion products are formed at high engine speeds owing to a lack of oxygen and sufficient temperature in the combustion chamber leading to the formation of CO emissions. Figure 5 depicts the variations of CO and engine speed and indicates that the increase in engine speed increases the Fuel concentration in the engine cylinder. This is explained by the lack of sufficient oxygen to aid in the complete combustion of the fuel molecules at high engine speeds which is identical to the study of (Ashok et al., 2019).

The variation of CO with two engine load modes (Mode 1, and Mode 2) and speed range of 500 r/min 25% engine load to 2000 r/min 100% engine load is shown in Figure 5. From the graph, it can be deduced that the engine speed, load and blend ratio increased, but there was a reduction of CO emissions up to intermediate engine speeds of 1500 r/min (Mode 2, 75 % of engine load). PD and all blends of WPPO such as 80/WPPO20, 70/WPPO30, 60/WPPO40 and 50/WPPO50; had values of 270ppm, 315ppm, 345 ppm, 370 ppm, and 398 ppm respectively. The highest value of CO emission reported was 485 ppm for blend 50/WPPO50 and the lowest value reported was for blend 80/WPPO20 at 315 ppm.

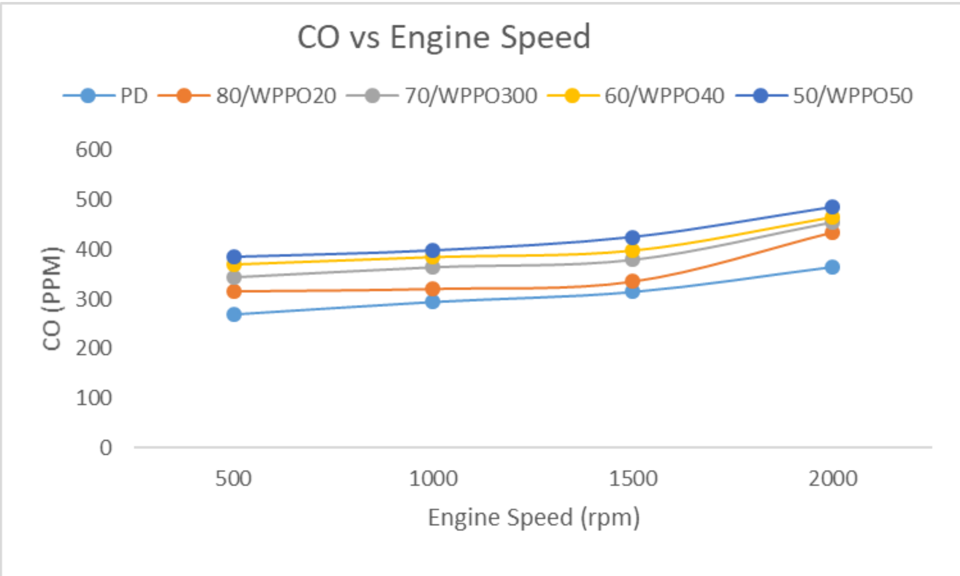

Figure 5. Carbon monoxide versus speed

As the engine approached full load (Mode 2, 2000 r/min), all the test fuels showed increased CO emissions with blends 80/WPPO20 and 70/WPPO30 reporting the lowest emissions value of 435 ppm and 455 ppm among the test blends across the entire engine load Modes 2 conditions.

According to data analyzed in this study several factors, explain the low CO emissions as the engine load and speed increase. The findings show the blends decreasing and increasing trends both for Modes 1 and 2 respectively as caused by the high viscosity prevalent in WPPO. The Viscosity of a fuel or blend automatically affects the spray pattern. High viscosity leads to poor fuel mixing hence incomplete combustion with increased carbon monoxide emissions (Ghurri, Kim, Kim, Jung, & Song, 2012; Hawi et al., 2019). This phenomenon is linked to the increased engine load and the short ignition delay, hence increasing CO emissions. Additionally, the decrease in CO emissions at low engine speeds (Mode 1 - 500 to 1000 rpm) could be due to the conversion of CO to CO_2 taking due to the high oxygen content present in biodiesel (Rahman et al., 2014). On the other hand, the Higher cylinder pressure and temperature influenced complete combustion as the engine speed increased, hence the reduction in the amount of CO emission (Soudagar et al., 2021).

Unburnt Hydrocarbons (UHC)

Due to poor atomization after injection, overleaning zones and wall flame quenching (Hariharan, Krishnan, Srinivasan, & Sohail, 2021; Heywood, 2018) results in exhaust emissions of UHC. Figure 6 is a variation of UHC emission with engine speed. As the engine speed increased in both modes, the UHC emissions increased too. However, the increase was more significant as the engine speed was in intermediate loads Mode 1 and Mode 2, 1000 r/min to 1500 r/min full load (50 % to 75 %) respectively. For example, at Mode 1, (1000 r/min, 50 % engine load), the blend values were 21ppm, 26ppm, 28 ppm, 30ppm, 33ppm respectively. compared to full load Mode 2 2000 r/min) at 11ppm, 15 ppm, 18ppm, 20ppm, and 23 ppm for CD and blends, 80/WPPO20, 70/WPPO30, 60/WPPO40 and 50/WPPO50 respectively.

The higher blend ratios 80/WPPO20, and 70/WPPO30 produced lower UHC emissions compared to other test blends. However, compared to CD test fuel, the trends in Figure 6 show high emission values for all blend ratios compared to the CD test fuel values. On the other hand, increased blend ratios significantly reduced UHC emissions across all the test blend ratios fuels irrespective of the engine Mode under test. This reduction can be explained by the high oxygen of WPPO which has an oxygen content value of 7.83 as in Table 7 and Figure 6 of the results and discussion.

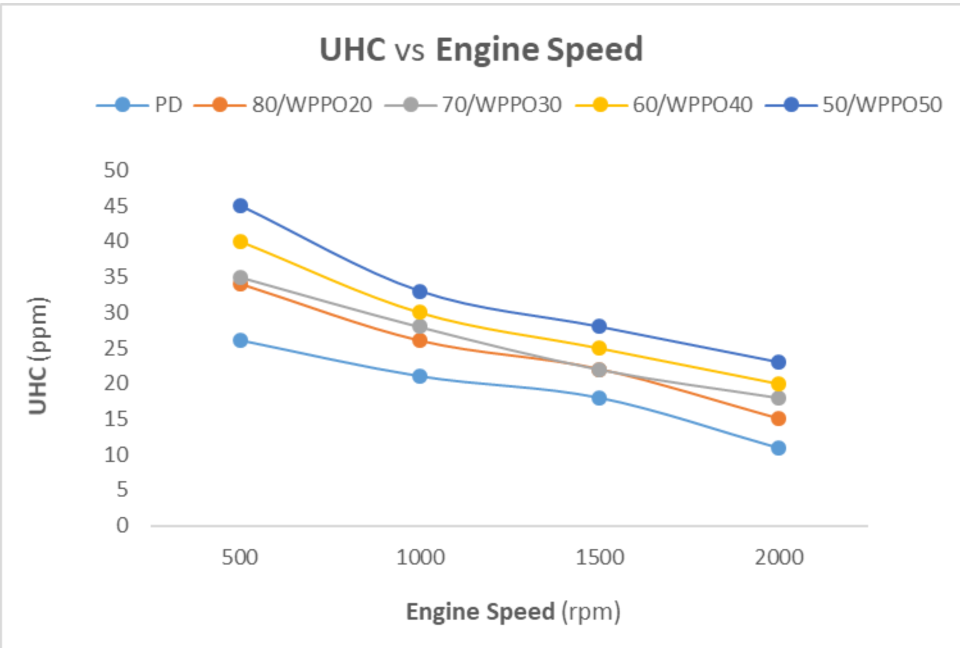

Figure 6. Unburnt hydrocarbons versus speed.

Figure 6 shows a significant increase in hydrocarbon emissions across all higher blend ratios. There are two main causes of this increased hydrocarbon emissions. The first reason is due to the presence of hydrogen radicals in diesel-WPPO blends and the higher aromatic compounds (Murugan, Ramaswamy, & Nagarajan, 2008). Other contributing factors include high density, low viscosity and low cetane number of WPPO blends. The result leads to poor spray characteristics of the test blends, leading to wall impingement and, thus high

UHC emissions. Several researchers such as (Lujaji, Kristóf, Bereczky, & Mbarawa, 2011; Maroa & Inambao, 2020; Tutak, Lukács, Szwaja, & Bereczky, 2015) have identified High blend ratios as a leading factor influencing the formation of UHC emissions using WPPO. Hence the conclusion is that high engine loads increase the values of UHC emissions proportionately to petroleum diesel. alternatively, the increment of pyrolytic fuel content in the blends or blend ratio increases ignition delay. This draws more heat and HC emission levels, hence increased UHC emissions (Khalaf et al., 2024). Additional influences of Increased UHC emissions are attributed to the engine operating environment especially if the temperature ranges of 400 ℃ to 600 ℃ exist in the combustion chamber. The main cause of the above phenomenon is the diesel exhaust pipe reaction, which either lowers or increases the concentration of UHC (Sanli, Canakci, Alptekin, Turkcan, & Ozsezen, 2015; Shirneshan, 2013).

3.5 Oxides of Nitrogen (NO_X)

NO_X emissions in internal combustion engines are a function of in-cylinder temperature and atmospheric nitrogen, at 78 % during intake. Besides NOx emissions are additionally a function of three main mechanisms in the combustion theory (Heywood, 2018; Stephen, 2000). Figure 7 shows the engine idling speed with NO_X emissions. Figure 7 shows that as the engine idling speed was increased it corresponded to an increase in the NO_X emissions irrespective of fuel blend ratio. The values of NO_X emissions for the blends 80/WPPO20, and 70/WPPO30 reported higher values at (Mode 2, 75 % load) compared to Mode 1. For example, at 1500 the values of the blends were 358 ppm, and 378 ppm, compared to PD fuel at 300 ppm respectively.

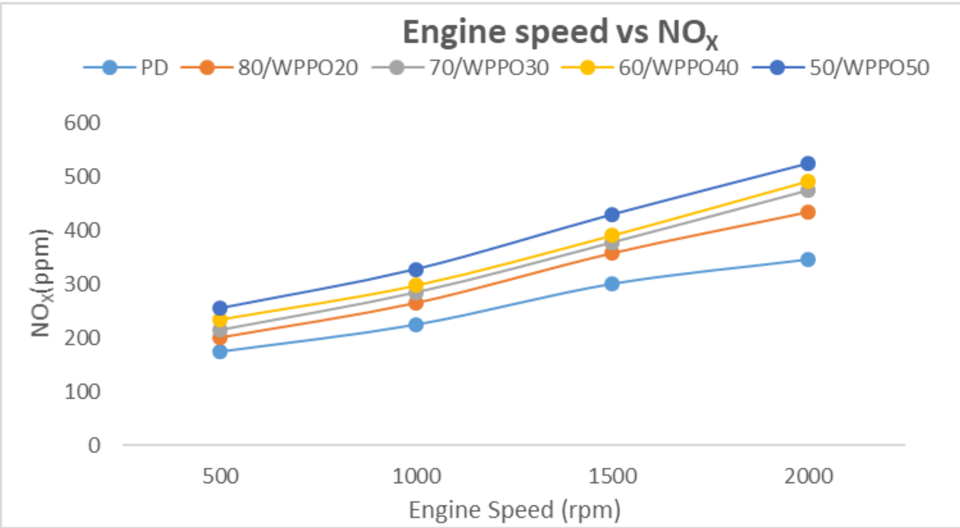

Figure 7. Oxides of nitrogen emissions versus different engine speeds

Blends 60/WPPO40 and 50/WPPO50 had the highest NO_X emissions compared to the other blends across all the engine speed conditions tested. At 500 r/min 25% engine load (Mode 1), the two blends (70/WPPO30, 60/WPPO40) had values of 215ppm and 235ppm respectively. However, at full speed (2000 r/min, 100% engine speed (Mode 2) the NO_X emissions for the two blends increased to 475ppm and 490ppm respectively compared to blends 80/WPPO20 with 435ppm.

The increase in the blend ratio in Figure 7 shows a direct increase in emissions of NO_X across all the blended fuels. However, blend 80/WPPO20 reported the lowest values of NO_X emissions at all engine speeds compared to all the other experimented and tested blend ratios. As earlier mentioned, NO_X in biodiesel fuel combustion strongly depends on the combustion temperatures and the oxygen concentration in the combustion zone. For example, high blend ratios of 70/WPPO30, 60/WPPO40 and 50/WPPO50 showed a shortened combustion process. A shortened combustion process led to a poor cooling effect and increases in peak combustion temperatures hence increased NO_X emissions. From the experiment and in the literature reviewed WPPO blends emitted higher NO_X due to the higher cetane index compared to diesel fuel. A high cetane index number results in a shorter ignition delay which means combustion constituents stay longer at elevated chamber temperatures, hence higher NO_X compared to PD.

These findings are identical to that study of (Cassiers et al., 2020; Hoekman, 2020; Hoekman & Robbins, 2012), who has reported extensively on the factors of The increased NO_X emissions due to the presence of increased cetane index and other contaminants from the WPPO biodiesel impurities. Additionally, high NO_X from this experiment could be due to the generation of radicals of hydrocarbons through molecular unsaturation in the blends, which is identical to the findings of (Altun, 2014; Varghese, Saeed, Lu, & Rutt, 2022). Finally, from this experiment increased emissions of NO_X could be due to elevated chamber temperature during the combustion process of these blends. Elevated temperature improves combustion linked to the high oxygen content and the air-fuel ratio factors but increases NO_X emissions (Devan & Mahalakshmi, 2009).

Conclusion

The following are the main conclusions based on the experiment work conducted on DICI Diesel Engine:

- Under the BSFC it was observed that, at high engine loads the conversion of heat energy to mechanical energy increased with an increase in combustion temperature, leading to increased BSFC for the biodiesel blends. The increase was proportional to the heating values of the different test fuels.
- During this experiment it was observed that biodiesel blends suffer from high mass injection pressures, hence increasing the BSFCs of blends. This is mainly due to the increased densities of the biodiesel blends used in the experiment.
- 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. This increase in fuel consumption was apparent in all blends utilized, 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 increase BTE as seen in intermediate loads of 1000 r/min 50% engine load to 1500 r/min 75% engine load for all the high blend ratios utilized.
- Results obtained during this experiment show that the BTE increased as the load increased. This is explained by the reduction in heat loss as the engine power (more fuel) increases 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 an 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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