

Influence of Exhaust Gas Recirculation and Emission Characteristics of a Diesel Engine Using Pyrolyzed Waste Plastic Biodiesel and Blends

Semakula Maroa¹ and Freddie Inambao²

^{1,2} University of KwaZulu-Natal, Durban South-Africa.

Abstract

Waste plastic pyrolysis biodiesel fuels have characteristics and qualities which are identical to conventional petroleum fuels. This work studied the influence of exhaust gas recirculation (EGR) on performance and emission characteristics of a diesel engine using biodiesel from Pyrolyzed waste plastics and blends compared to conventional diesel. There are a limited number of experimental works on waste plastic pyrolysis, especially the interaction, influence and effects of EGR on diesel engines. The results show that the amount of carbon monoxide (CO) emissions seemed to decrease at low engine loads up to intermediate loads (50 %), thereafter continued to increase significantly and marginally. Among the blends WPPOB100 reported the highest BSFC with a value of 0.4751 g/kW.hr at 0 % EGR flow rate compared to 0.7235 g/kW.hr at 30 % EGR flow rate. The increase in blend ratio showed a direct decrease in brake power (BP) in a linear relationship. At 30 % engine load conventional diesel (CD), WPPOB10, WPPOB20, WPPOB30 and WPPOB40 had values of 2.125 kW, 2.15 kW, 2.05 kW, 1.98 kW, 1.86 kW and 1.75 kW respectively. Regarding exhaust gas temperature (EGT), the WPPOB10 blend at 30 % EGR flow rate had the greatest reduction in temperature compared to the other WPPO blends with a temperature value of 320 °C. For unburnt hydrocarbon (UHC) emissions, EGR flow rates of CD at 5 %, 10 %, 15 %, 20 %, 25 % and 30 %, had 43 ppm, 57 ppm, 70 ppm, 82 ppm and 85 ppm respectively, compared to WPPOB10 whose values were 23 ppm, 35 ppm, 40 ppm, 48 ppm, 50 ppm, and 52 ppm respectively. All the fuels tested indicated a drop in nitrogen oxide (NO_x) emissions with an increase in the application of EGR % flow rate, at all engine load conditions. The WPPO blends were observed to produce a continuous increase in smoke emission to almost double the values with the application of EGR flow rate. At 10 % CO emission values were 9.79 %, 10.46 %, 10.91 %, 11.25 % and 12.75 % for WPPO10, WPPO20, WPPO30, WPPO40 and WPPO100 respectively. The higher the blend ratio and the higher the increase in EGR % flow rates, the higher the carbon dioxide (CO₂) emission values and vice versa. At 30 % EGR flow rate the CO₂ emissions for CD were 10.95 % compared to WPPOB10 9.95 %, WPPOB20 9.65 %, WPPOB30 8.85 % with WPPOB100 showing the highest value of 14.35 %. Increased blend ratio and EGR % flow rate showed a steady increase in the smoke emissions within the test fuels with marginal decreases observed across all the blended fuels. At 15 % EGR flow the values were 7.53 %, 7.1 %, 6.72 %, 6.25 %, 6.0 % and 5.4 % for CD, WPPO10, WPPO20, WPPO30, WPPO40 and WPPO100 respectively.

Keywords: Biodiesel, EGR Flow Rate, NO_x, Smoke Emissions, pyrolysis, waste plastic oil

ABBREVIATIONS

R _x	Molar Gas Ratio
n _f	Fuel Molar Quantity
Al ₂ O ₃ ,	Aluminium Tri-Oxide
ASTM	American Society for Testing and Materials
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CaO	Calcium Oxide
CD	Conventional Diesel
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
Cu	Copper
DEA	Department of Environmental Affairs
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FBP	Final Boiling Point
G-20	Group of 20 Highly Industrialized Countries
G-7	Group of 7 Developed and Industrialized Countries
GC-MS	Gas Chromatography Mass Spectrometry
GVC	Gross Calorific Value
HPDE	High-Density Polyethylene
HRR	Heat Release Rate
IBP	Indicated Brake Power
SiO ₂	Silica Dioxide
kW	Kilowatt
LPG	Liquid Petroleum Gas
LTC	Low Temperature Combustion
MSW	Municipal Solid Waste
NaAlSi ₂ O ₆ -H ₂ O	Zeolite

NO _x	Oxides Nitrogen
PEHD	Polyethylene High-Density
PM	Particulate Matter
PVC	Poly Vinyl Chloride
UHC	Unburnt Hydrocarbons
WPPO	Waste Plastic Pyrolysis Oil
<i>x</i>	Exhaust Molar Gas Quantity
<i>y</i>	Inlet Intake Molar Gas Quantity
<i>z</i>	Remainder of the Intake Charge

INTRODUCTION

The importance of modern day transport systems cannot be overstated, especially the transportation of goods and services and people. The propulsion provided by internal combustion engines with diesel fuel as the primary source of energy forms the bulk of commercial use and personal transport, owing to their numerous advantages of this fuel. Diesel engines are inherently lean burn engines, and emit relatively low carbon dioxide (CO₂) emissions compared to petrol propelled internal combustion engines. Other advantages offered by diesel engines include high thermal efficiencies, durability and construction robustness [1]. These advantages mean that the use of such engines is increasing as more countries move into urbanization and industrialization and catch up with the highly industrialized countries. However, there is now a challenge to phase them out based on environmental and human health issues due to the high levels of nitrogen oxide (NO_x), smoke and particulate matter (PM) emissions.

There has been an increase in stringent emission regulations enacted by global industrial powers such as the United States of America, the European Union and the G-7 and G-20. Diesel engines have been identified as a major source of pollution due to their emission of NO_x gases, so now alternative fuels are being sought in the interest of reducing energy consumption as well as reducing environmental degradation. The rapid expansion of the road transport industry sector is fast eroding all the technological developments and improvements thus far achieved in the war against pollution from diesel propelled engines. Issues relating to climatic change, uncontrolled or erratic energy prices, uncertainty of future fossil fuel supplies [2] and unending internal conflicts and war in major oil producing countries create a very compelling case for alternative fuels.

Due to the increase in food insecurity the production of biodiesel fuel from plant based stocks is a less viable option because of its impact on higher food prices [3]. Therefore, waste plastic from municipal solid waste management sites is increasingly being considered as an alternative source of fuel and energy due to the widespread availability of plastics and their cost of disposal and negative effect on the environment. There are two types of plastics widely used today, namely: PVC (poly-vinyl chloride) and HPDE (High-density polyethylene) also known as polyethylene high-density (PEHD) [4]. Plastic

waste wreaks havoc on the environment because plastics are petroleum based which makes them non-biodegradable [5]. Plastic waste accounts for between 8 % to 12 % of global waste with a projected increase of between 9 % to 13 % annually by the year 2025 [6] and [7]. According to a study conducted in India, nearly 5.6 million metric tonnes of plastic waste are generated every year out of which only a paltry 10 % is recirculated, while 80 % goes into landfills which causes pollution. In South Africa 24 115 402 metric tonnes of general waste is produced annually, of which 6 % (1 446 924 metric tonnes) was plastic waste with a national average waste production annual increment projection of 2 % to 3 % since 2008 [8], as shown in Figure 1. These figures support the case for using technology to degrade waste plastic mass into energy. Techniques such as pyrolysis can yield hydrocarbons similar in quality and characteristics to petroleum fuels [9] and [10].

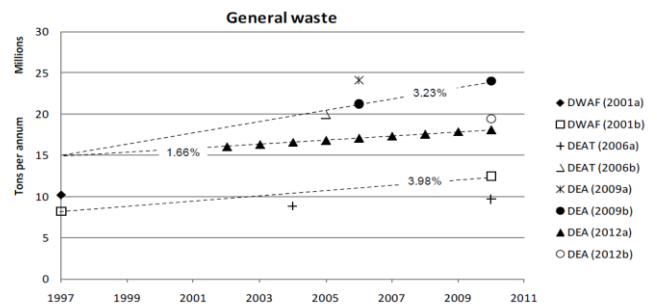


Figure 1 Analysis of available general waste data (from municipalities) in South Africa [8]

Pyrolysis is a word originally coined from two Greek words pyro “fire” and lysis “decomposition” [11]. It is a chemical decomposition process which makes fuel from plastic waste by heating and has been commended by [12] as one of the solutions to management of the menace of plastic waste. During the pyrolysis process, assorted waste plastics are introduced and fed into a reactor and subjected to high temperatures of 400 °C to 600 °C and sometimes up to 900 °C at atmospheric pressure in the absence of oxygen for 3 to 4 hours [13] to produce oil and other by-products. In order to maintain and sustain high temperatures during the pyrolysis reaction, [14] catalysts are therefore employed, including calcium oxide (CaO), silica dioxide (SiO₂), aluminium tri-oxide (Al₂O₃) and zeolite (NaAlSi₂O₆-H₂O) [15]. This process breaks down large molecules of waste into minute molecules resulting in hydrocarbons with a smaller molecular mass. For example, the addition of ethane enables fractional distillation to be applied and to obtain fuels, chemicals and by-products from the process. Pyrolysis as a process gives yields with a weight factor of 75 % of liquid hydrocarbons in a mixture of petrol, diesel and kerosene, 5 % to 6 % as residue coke and the remaining balance as liquefied petroleum gas (LPG) [16]. Pyrolysis as a method of producing waste plastic biodiesel is highly recommended by most researchers and commercial entities because of its cost effectiveness and its high energy conversion rate, besides the high yield when compared to any other method of plastic waste energy extraction [17].

The use of biodiesel calls for NO_x reduction techniques such as exhaust gas recirculation (EGR) due to the oxygen content inherent in most biodiesel fuels which is the single most important factor responsible for NO_x formation as it reacts with high temperature combustion mixtures thereby increasing the availability of NO_x [7]. Diesel fuels and biodiesel fuels both require fuel additives to improve engine lubricity, better ignition qualities and better mixing. Oxygenates in biodiesels are providing a promising future to reduce PM emissions since the O₂ content aids in better combustion, besides lowering exhaust emissions with a clear trade-off between PM and NO_x as suggested in the findings of [18], [19] and [20]. Most researchers suggest modifications, for example thermal barrier coating by [21], where efficiency is improved, and NO_x emissions and smoke density are reduced with a minimal increase in brake thermal efficiency (BTE), although fuel economy may drop.

[22] Observed that with the application of EGR % flow rate a further reduction for both NO_x and soot emission can be achieved when n-pentanol is added. [23] observed a simultaneous reduction for both NO_x and soot emissions using a low temperature combustion (LTC) strategy, with application of EGR % flow rates coupled with late injection timing and addition of n-pentanol to the blended diesel biodiesel tested. However when [24] added n-pentanol to the diesel biodiesel the brake specific fuel consumption (BSFC) increased with no increase in BTE. This seems to confirm n-pentanol as a better fuel additive for waste plastic pyrolysis oil (WPPO) compared to n-butanol due to its high cetane number, better blend ratio stability and less hygroscopic nature as observed by [25].

Other methods that have been suggested include reduced ignition delay, which reduces combustion temperatures, thus aiding in the reduction of NO_x as its formation is temperature dependent. The use of cetane improvers is also an alternative for reducing NO_x as the poor cetane index of WPPO fuel blends leads to poor ignition quality, particularly when biodiesel fuels are used such as glycol ether which reduce PM, unburnt hydrocarbons (UHC) and CO emissions especially in common rail direct injection diesel engines. Cetane improvers also decrease cylinder pressure, ignition delay, heat release rate, and engine knock or noise [26]. The inclusion of n-pentanol in diesel biodiesel blends was observed by [27] to shorten combustion duration and increase the heat release rate (HRR), while significantly reducing the NO_x, CO and UHC emissions.

Fuel additives have also been suggested and used, with the most commonly used being diethyl ether. As an organic compound diethyl ether has a high cetane number and is capable of boosting ether compounds' cetane numbers as an improver [28]. In their study Devaraj et al. found that when used as an additive diethyl ether reduces ignition delay, cylinder peak pressure, HRR, CO, CO₂ and NO_x with a trade off in BTE which was observed to be increased. [29] on the other hand found diethyl ether to reduce the ignition delay period, UHC, and NO_x whereas BTE seemed to be increased, but [14] using WPPO fuel observed and reported ignition delay and higher HRR with diethyl ether.

Diesel engines have been shown to run stably on most medium blended ratios of waste plastic oil, although they produce more

NO_x, UHC and CO emissions. In order to stabilize them and the performance of higher blend ratios, injection timing has been proposed without the need for upgrading the fuel, engine modification or fuel alteration through addition of additives as observed by [30]. Injection timing was seen to affect performance from WPPO in the study by Sharma et al. [31], where Jatropa blends of 20 % tyre oil and 80 % Jatropa ester oil resulting into lower fuel consumption, CO, UHC and PM although it was observed to increase NO_x emissions. [32] Observed an increase in the BTE and NO_x emissions, thus concurring with the findings of Sharma et al. on emissions of NO_x, although on fuel consumption, CO, and UHC they noted decreased results. This work will endeavour to study the influence of EGR on the performance of a diesel engine using a biodiesel fuel derived from pyrolysis of waste plastic, and how WPPO interacts with engine performance and emission characteristics when EGR is applied.

EXPERIMENTAL

Experimental Apparatus and Equipment

Figure 1 is a schematic diagram for the experimental engine set-up and its components, which were used in the experiment. Figure 2 is another schematic diagram showing the modification of the EGR loop that was adapted for the experimental engine in Figure 1. Table 1 is the experimental engine specification standards of the experimental engine that was used throughout the study

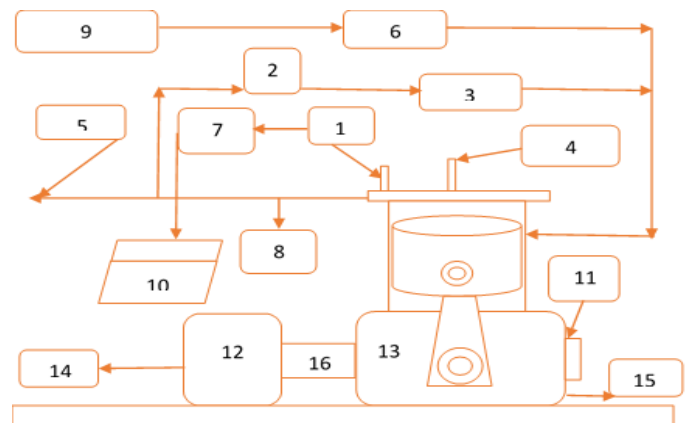


Figure 2. Experimental test engine test rig set-up diagram

Key: 1. Cylinder pressure sensor, 2. EGR control valve, 3. EGR cooler, 4. Injection Control Unit, 5. Exhaust gas exit, 6. Air box, 7. Signal amplifier, 8. Gas analyser, 9. air flow meter, 10. Data acquisition system, 11. Crank position sensor, 12. Dynamometer, 13. Engine, 14. Air flow rate meter, 15. Cooling water exit to the cooling tower, 16. Dynamometer drive coupling.

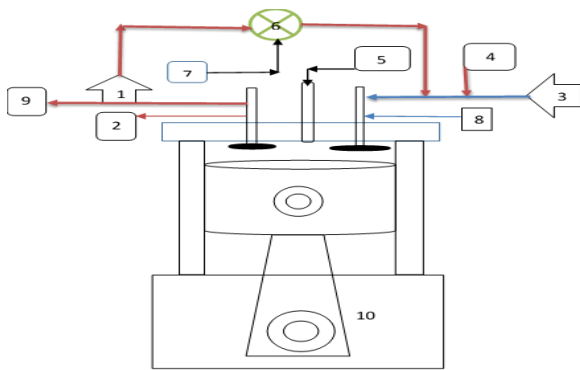


Figure 2. EGR schematic loop modification

Key; 1. The direction of EGR gases, 2. The x subscript representing the exhaust molar gas quantity, 3. The direction of inlet gases fresh charge, 4. The z subscript representing remainder of the intake charge, 5. n_f Which is the fuel molar quantity, 6. The EGR valve, 7. The R_x molar gas ratio, 8. The subscript y representing the inlet intake molar gas quantity, 9. The direction of the exhaust gases exit, 10. The engine unit

Table 1. Engine specifications, position value and type

Parameters	Position value
Ignition Type	4 (Stroke) DIC1
Number of Cylinders	1
Model	TV 1
Cooling Medium	Water
Manufacturer	Kirloskar
Revolutions Per Minute	1500
Brake Power	3.5 Kw
Cylinder Bore	87.5 mm
Piston Stroke	110 mm
Compression Ratio	18.5:1
Connecting-Rod Length	234
Engine Capacity	661cc
Dynamometer Make	234
Injection Timing	23.4° bTDC
Maximum Torque	28 N-M@1500
Injection Pressure	250 Bar

Waste Plastic Preparation and Conversion Process

The waste plastic materials were acquired from a municipal waste management site in Durban. The waste plastic is first sorted in a section of the pyrolysis plant. The dust and other fine waste from the sorted plastic waste materials is collected by the cyclone filter and disposed of through a vent with a particle size monitoring system within the plant. After the sorting and removal of unwanted materials and dust, the waste plastics are taken through a conveyor machine to a pressure cleaner for thorough cleaning, after which they are conveyed to a shredding machine which reduces them to the required size

of 25.4 mm to 50 mm, suitable for the pyrolysis reactor. The waste material is then loaded into the pyrolysis reactor by means of an automatic feeding machine, although there is provision for manual loading in case there is a system failure. Before starting the pyrolysis, the airtight reactor door is locked. The system is started from a control panel by a machine operator with the preceding processes subsequently running automatically as indicated by the flow chart in Figure 3. The first stage is to heat up and dry the waste plastic materials and increase the reactor temperature to the required value of 400 °C to 500 °C. The heavy dense gas oil falls into the oil tank while the light oils rise up into the condenser where they are cooled and taken back into the oil tank for collection.

The liquefied gases in small quantities which cannot be converted into oil are recycled and collected by the recycling system to be burnt as fuel gas or cleaned through the after-treatment system with the smoke and flue emitted by the plant being released to the atmosphere after the removal of sulphurets and black carbon. After the pyrolysis process is over the system requires a cooling period of 4 hours to 5 hours through natural cooling, but nitrogen and carbon dioxide gases can be used as cooling agents to reduce the cooling waiting time. This enables the removal of the carbon black compound without contamination and pollution to the environment. The final operation is the removal of steel and other metals obtained in the pyrolysis reactor plant, as this requires the opening of the reactor door in preparation for the next batch of the pyrolysis process.

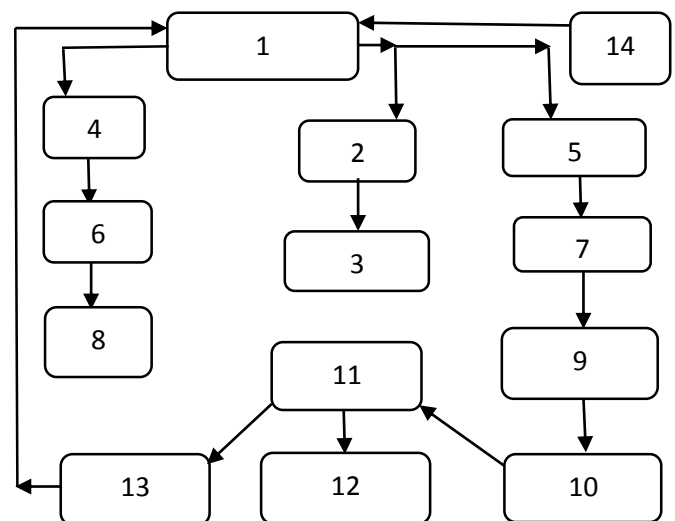


Figure 3. The waste plastic pyrolysis oil processing plant flow chart.

Key: 1. Pyrolysis reactor, 2. Carbon black discharge, 3. Carbon black deep processing, 4. Exhaust smoke discharge, 5. Gas separator, 6. Smoke scrubber to take out colour and odour, 7. Condenser, 8. Chimney, 9. Oil tank, 10. Synchronized gas purification, 11. Synchronized gas recycling system, 12. Extra gas burning, 13. Heating furnace during operation, 14. Loading of material section.

Physical Properties of Waste Plastic Pyrolysis Oil (WPPO) Sample

Table 2. The test fuel properties, their units of measurement, standard methods of testing and the values for conventional diesel in comparison to the values of waste plastic pyrolysis oil

Property	Unit	CD	WPPO	STANDARD
Appearance	-	Clear/brown	Clear/amber	Visual
Density @ 20	kg/M ³	838.8	788.9	ASTM D1298
Kinematic viscosity @ 40 ° C	cSt	2.32	2.17	ASTM D445
Flash point	° C	56.0	20.0	ASTM D93
Cetane index	-	46	65	ASTM D4737
Hydrogen	%	12.38	11.77	ASTM D7171
Cu corrosion	3 hrs @ 100 ° C	-	1B	ASTM D130
Carbon	%	74.99	79.60	ASTM D 7662
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	kJ/kg	44.84	40.15	ASTM D4868

Table 2 shows the results of the physical properties of the WPPO obtained through the pyrolysis process of the waste plastics from municipal solid waste (MSW) management sites, at optimized conditions and compared to the properties of CD fuel oil. The appearance of the oil is yellowish in colour as shown by the photo in Figure 4 and the liquid distillate is free of visible particulate sediments with a flash point of 20 ° C, and a gross calorific value (GCV) OF 40.15 KJ/kg which almost compares to the range indicated by most petroleum fuels including CD, thus making it capable of giving the same working performance results in internal combustion engines, especially diesel propelled ones.



Figure 4. The distillate samples from the waste plastic pyrolysis oil samples

The distillation report analysis shows the WPPO has an initial boiling point (IBP) of 119 ° C to 353.5 ° C, thus indicating some presence of other fuel oil components like kerosene,

gasoline and to some extent diesel oil in the tested samples. This leads to the observation and conclusion that it is possible for this oil to be used as a feedstock in future, if it is upgraded into a lighter compound such as diesel fuel or any other liquid fuel in the foreseeable future.

Table 3 shows the chemical composition of the WPPO from a pyrolysis plant process.

Table 3. Chemical composition of the WPPO obtained from a GC-MS laboratory analysis report

Molecular formula	Percentage composition
C ₁₀	66.32
C ₁₀ -C ₁₅	4.38
C ₁₅ -C ₂₀	12.66
C ₂₀ -C ₂₅	8.22
C ₂₅ -C ₃₀	8.42

Experimental Procedure

The engine employed for this work was a Kirloskar experimental variable compression engine, four stroke single cylinder, water cooled developing 3.75 kW of power at 1500 rpm. The schematic is provided and shown in Figure 1. The technical specifications of the experimental variable compression engine are shown and indicated in Table 1. A

dynamometer was used to provide the engine with load during the experimentation, and to get measurements for the engine intake air flow an air box was fitted to the engine intake manifold system with a standard orifice mechanism. The fuel flow rate to the experimental engine was measured using a digital fuel gauge with a stop watch mounted to measure time taken for the fuel to be consumed.

The exhaust gas temperatures were measured using mounted temperature thermocouples of k-2 type, including the EGR temperature which is measured before it mixes with the intake fresh air charge and the constituents of the combustion chamber, through the same k-2 thermocouples. A cylinder pressure transducer was mounted on the engine cylinder head to monitor cylinder combustion pressure and collect data values through a system charge amplifier connected to a computer data acquisition machine. The crankshaft position or the crank angle was monitored and measured through a mounted encoder near the crankshaft pulley area. The emission gases during the experiment were monitored through a five gas exhaust gas analyser, while to measure the smoke intensity an AVL 437C smoke meter was employed.

Since the engine develops maximum power at 1500 rpm and it is a variable compression engine, all the experiments were conducted based on this nominal engine speed at part load and full load, but data could be obtained from different engine loads. Part engine load is described as 50 % of engine load and full engine load is described as the engine running at 100 % load, with a fixed compression ratio of 18.5:1. The EGR system is shown in Figure 3, modified to suit the experimental engine and enable data collection. The exhaust gases were tapped from the exhaust pipe and joined to the intake manifold air intake system via the air flow meter box through a manually controlled gate valve which made it possible for the mixing of EGR gases and the fresh air intake.

The EGR % flow rate was divided into the following modes: 0 %, 5 %, 10 %, 15 %, 20 %, 25 %, and 30 % spaced at intervals of 5 %. The waste plastic pyrolysis oil fuel blends were prepared in the following percentage order and mixed with CD fuel 10 %, 20 %, 30 %, 40 % and 100 %, where the WPPO10 blend is 90 % CD fuel and 10 % WPPO fuel in that order.

Throughout this experiment blends will be referred to in this format with digits denoting the percentage blend ratio of WPPO by volume to CD supplied. To avoid experimental fuel from being contaminated from the previous test, each test was conducted after a thorough evacuation procedure was conducted on the fuel lines and the fuel injection system mechanism of the test engine. This made it possible to conduct an experiment and collect good data and measurements with inputs from the test mode only, without fear of contamination and poor results from error.

Analysis of Error and Percentage Inaccuracies

This process was carried out for the purpose of performing and identifying the accuracy and precision of the measuring tools and instruments used in this experiment work, as errors can occur due to conditions outside of the experiment itself, such as calibration of the instruments, observational errors, manufacturing errors, errors associated with experimental set-up and planning, besides environmental conditions existing during the experiment [33]. The list of instruments used and their percentage error of analysis are provided in Table 4 together with the percentage inaccuracies of CO, CO₂, UHC, NO_x, EGT and smoke opacity.

The percentage of error analyses are derived from the following formula, the root sum square method and expressed in equation form [1] as:

$$R = \sqrt{\sum_{i=1}^n X_i^2} \quad \text{Equation 1}$$

Where R is the total uncertainty percentage, X_i is the individual uncertainty of all the calculated operating parameters, n is the total number of the parameters in the experiment and i is the i^{th} term of the computed parameters. The total percentage of the uncertainty is thus calculated based on Equation 2 as follows:

$$R = \sqrt{X_1^2 + X_2^2 + X_3^2 + \dots + X_i^2} \quad \text{Equation 2}$$

Table 4 shows the instruments used for measurements and data collection, their measuring range, accuracies and percentages of inaccuracies, as calculated from Equation 2.

Table 4 Instruments used for measurements and data collection

Instrument	Accuracy	Measuring Range	Percentage inaccuracies
AVL 437C smoke meter Smoke intensity	± 1 %	0-100 %	± 1
AVL pressure transducer GH14D	± 0.01 bar	0-250 bar	± 0.01
AVL 365C Angle encoder	± 1°	-	± 0.2
AVL Digas 444 (Five Gas Analyser)			
CO	± 0.03 % to ± 5 %	0-10 % by vol	± 0.3
CO ₂	± 0.5 % to ± 5 % by vol	0-20 % vol	± 0.2
O ₂	± 5 % by vol	0-22 % by vol	± 0.3
HC	± 0.1 % to ± 5 %	0-20000 ppm by vol	± 0.2
NO _x	± 10 %	0-5000 ppm by vol	± 0.2

Instrument	Accuracy	Measuring Range	Percentage inaccuracies
K-2 Thermocouple	$\pm 1^{\circ} \text{C}$	0-1250 ^o C	± 0.2
Digital Stop Watch	$\pm 0.2 \text{ s}$		± 0.2
Digital Fuel Gauge	$\pm 1 \text{ mm}$		± 2
Burette	$\pm 0.2 \text{ cc}$	1-30 cc	± 1.5

3.0 RESULTS AND DISCUSSION

3.1 Brake Specific Fuel Consumption (BSFC)

Figure 5 shows the variation of the BSFC under the effects of EGR % flow rate with different fuel blends of WPPO and CD operating at full engine load conditions.

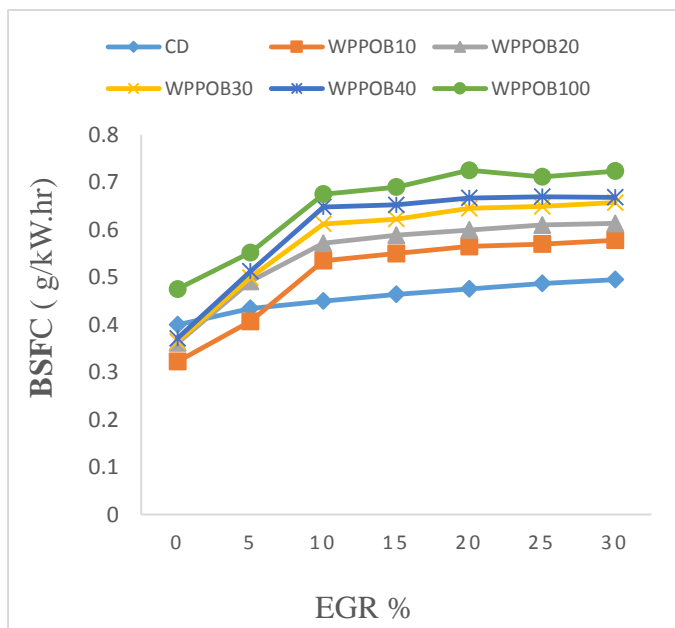


Figure 5. Brake specific fuel consumption (BSFC) versus EGR % flow rate

As can be seen from Figure 5, the lower ratio blends of WPPOB10 and WPPOB20 showed minimal reduction in BSFC at 0 % EGR flow rate compared to the values of CD and WPPOB100 which showed significantly higher values of BSFC at that mode. At 0 % EGR flow rate CD had a BSFC value of 0.4 g/kW.hr compared to WPPOB100 with a value of 0.4751 g/kW.hr, indicating that the fuel blend WPPOB100 had a higher BSFC than CD and the other blends of WPPO at 0.3225 g/kW.hr, 0.3615 g/kW.hr, 0.3645 g/kW.hr and 0.3715 g/kW.hr, for WPPOB10, WPPOB20, WPPOB30 and WPPOB40 respectively.

A similar trend was noted under the influence of EGR % flow rate where for example at 20 % to 25 % EGR flow rate, the BSFC showed increased tendencies. These findings concur with the findings of [34]. This phenomenon can be explained due to the effects of dilution of the fresh air intake as it mixes with exhaust gases that are being recirculated through the EGR system which leads to incomplete combustion of the inducted mixture, thus leading to a drop in power and engine torque as

observed by the findings of [35]. This scenario forces the engine to increase its fuel consumption in order to maintain constant speed and its increased load hence the increase in BSFC.

The WPPO biodiesel blends with EGR % flow rate applications showed a better fuel economy, especially the lower blend ratios of WPPOB10 and WPPOB20, compared to conventional diesel test fuels. However, as the EGR % flow rate increased there was a noticeable increase in the BSFC across all the test fuels used. At 0 % EGR CD was 0.4 g/kW.hr compared to 30 % EGR flow rate which was 0.495 g/kW.hr. For the WPPO biodiesel WPPOB10 blend the value was 0.3225 g/kW.hr compared to 0.5780 g/kW.hr at 30 % EGR flow rate. From Figure 5 it is evident that the test fuel that showed the highest BSFC among the blends of diesel and the CD test fuel was WPPOB100 which at 0 % EGR flow rate had a value of 0.4751 g/kW.hr compared to 0.7235 g/kW.hr at 30 % EGR % flow rate.

An interesting observation during experimentation was that after the 10 % EGR flow rate the values for the BSFC across all the test fuel seemed to show and pick a lineal increment trend as can be shown in Figure 5 by the flattening of the graph curves and the close value trends.

Brake Thermal Efficiency (BTE)

BTE studies specifically help us to know the ability of the combustion system to accept the fuel provided and how efficient it is in converting that fuel and turning it into a mechanical output, as observed by [28] and [27].

Figure 6 shows the BTE % variations, under different blends of WPPO and conventional diesel fuel, with the application of EGR % flow rate.

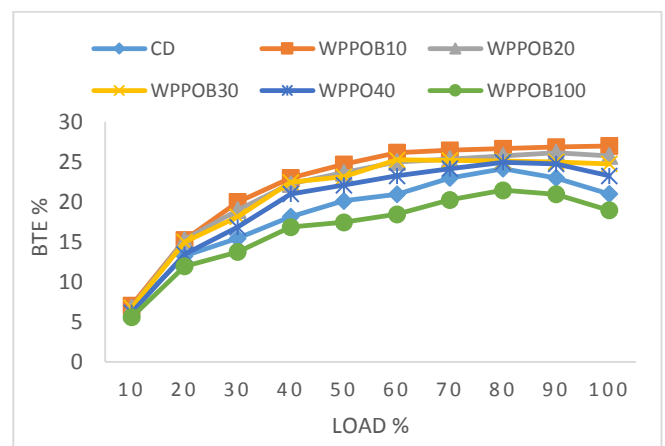


Figure 6 brake thermal efficiency (BTE) versus engine load %

Figure 7 shows the variation of BTE % with the application of EGR % flow rate using different blends of WPPO and CD.

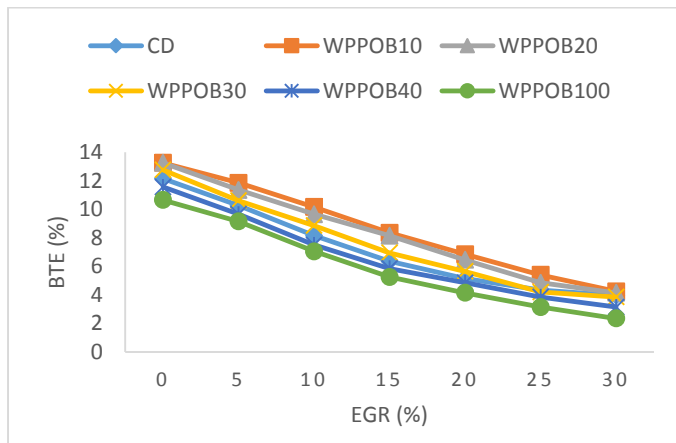


Figure 7. Brake thermal efficiency (BTE) % versus EGR % flow rate

From Figure 7 it is evident that there was a noticeable decrease in the BTE especially with all high ratio fuel blends of WPPOB40 and WPPOB100 compared to CD. In comparison to other WPPO blends WPPOB100 obtained the lowest decrease of BTE with a value of 7.05 % at 10 % EGR flow rate and the least value of 2.35 % at 30 % EGR flow rate.

Although there was a reduction in BTE due to the application of EGR % flow rate as shown in Figure 7, the trends of decreased BTE continued to be observed. For example, at 0 % EGR flow rate, the value of BTE for CD was 12.15 % compared to WPPOB10 and WPPOB20 with values of 13.25 % and 13.05 %. The WPPOB100 blend had the lowest value for BTE for all EGR rate flow modes than any other test fuel.

Brake Power (BP)

Figure 8 shows engine brake power (BP) variations with EGR % flow rate application with CD and different WPPO blends at full engine load conditions.

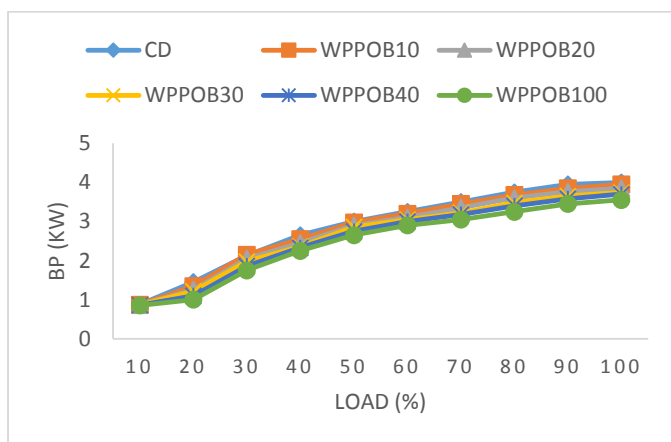


Figure 8. Engine brake power (BP) versus varying engine load %

The results in Figure 8 show that there was a lineal increase in BP for all the test fuels with an increase in the engine load. CD had the highest increase in BP values compared to the blended fuels of WPPO. At 20 % engine load, the BP value for CD was 1.45 kW while WPPOB10 had a value of 1.350 kW representing a difference of 6.8 % in BTE when the two fuels are compared.

The blended fuels in Figure 8 also show very close increments in BP with an increase in engine load conditions and a decrease in BP with an increase in the blend ratio for all the blended fuels tested. The increase in blend ratio showed a direct decrease in BP in a linearly incremental relationship. For example, at 30 % engine load CD, WPPOB10, WPPOB20, WPPOB30 and WPPOB40 had values of 2.125 kW, 2.15 kW, 2.05 kW, 1.98 kW, 1.86 kW and 1.75 kW respectively, showing a decrease in the value of the BP throughout the experimentation period. The WPPOB100 blend showed the lowest values for the BP compared to the blends of WPPOB10, WPPOB20, WPPOB30 and WPPOB40 used in this study. These findings concur with the findings by [19] in relation to WPPO blends.

The application of EGR % flow rate was observed to cause no significant change in BP. However, there was a negligible drop in the engine brake power with the influence of EGR flow rate except for the blend WPPOB10 which had almost identical value to CD as the curve of the two fuels indicate in Figure 8. This leads to the conclusion that the blends of WPPO have identical BP values with CD.

Exhaust Gas Temperature (EGT)

Figure 9 shows the variation of exhaust gas temperature under different types of WPPO blend and CD with application of EGR % flow rate.

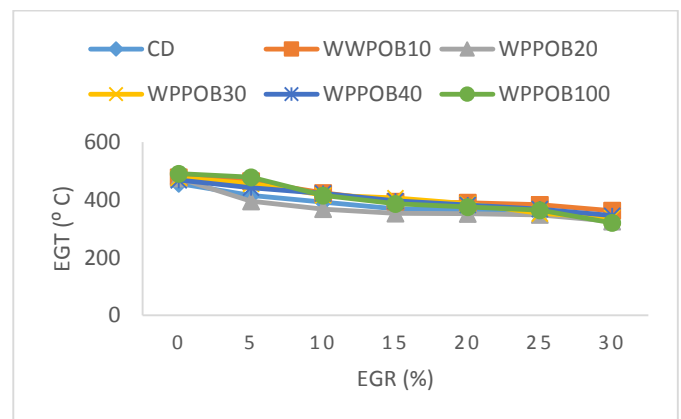


Figure 9. Exhaust gas temperature (EGT ° C) versus EGR % flow rate

Temperature is one of the key factors in determining the formation of engine exhaust emissions, besides providing or helping in the analysis and study of combustion processes in relation to fuel as observed by [36].

It is evident from the results in Figure 9 that there was a variation in EGT of WPPO and CD with the application of EGR

% flow rate. The results indicate that EGT decreased with different blends of WPPO compared to CD. The temperature difference between them was that WPPO blends had higher temperature increases in all the test conditions compared to CD. However, it should be mentioned that as the blend ratio increased with EGR % flow rate application, the EGT reduced significantly and marginally especially for WPPOB30 and WPPOB40. The highest temperature value obtained for CD was 456 °C at 0 % EGR flow rate, whereas the highest temperature value for WPPO blend was 490 °C obtained from WPPOB100 at 0 % EGR flow rate, although at 30 % EGR flow rate this blend had the most reduction in temperature compared to the other WPPO blends with a temperature value of 320 °C.

The application of EGR % flow rate in increasing modes brought further reduction in EGT with the highest value for CD obtained being 440 °C with an EGR % flow rate of 5 % while the minimum or lowest value of 340 °C was obtained at 30 % EGR flow rate. The WPPO blends showed a similar trend with decreasing temperatures with the application of EGR % flow rate with WPPOB10 showing the highest value of 467 °C and lowest of 362 °C at 5 % and 30 % EGR rate flow respectively, while WPPOB40 showed a highest value of 472 °C and a lowest of 330 °C at 5 % and 30 % EGR flow rate respectively.

The cause of the reduction in EGT can be attributed to several factors. The reduction in EGT among the different blends of WPPO is a result of low calorific value of the blends and the low exhaust loss, which concurs with the findings of [37] and [38]. The WPPO has a calorific value of 40.15 kJ/kg compared to the calorific value of CD at 44.84 kJ/kg as shown in Table 2. Other causes are directly linked to the effects of EGR rate flow, the dilution effect, chemical effects and thermal effects [39] and [40].

Unburnt Hydrocarbon (UHC) Emissions

Figure 10 shows the variation of UHC emissions in parts per million under full engine load with the application of various EGR % flow rates, and different blends of WPPO and CD. The UHC emissions were significantly higher across all the blended test fuels of WPPO, especially with higher engine load conditions as indicated by the values shown in Figure 10. However, CD produced more and higher values of UHC emissions compared to all the blends of WPPO across all the engine loading conditions and operating modes.

Figure 10 shows UHC emissions (ppm) values under engine load with different fuel blends of WPPO and CD under the effects of EGR % flow rate application.

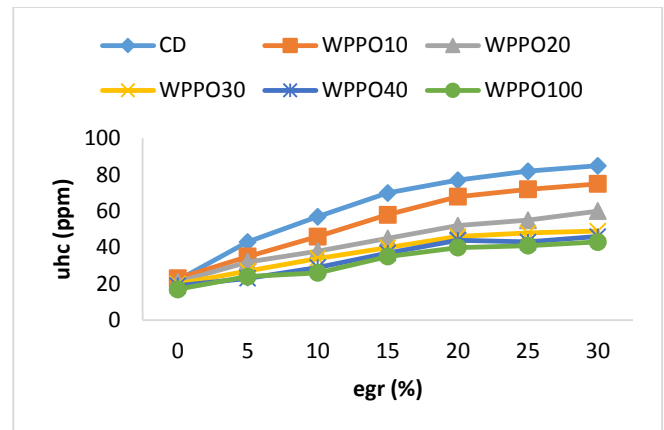


Figure 10. Unburnt hydrocarbons (UHC) emissions versus EGR % flow rate

As can be seen from Figure 10, when the EGR % flow rate application was 0 %, there was no application effect. Figure 10 shows that there were less UHC emissions for all the test fuels applied in this experiment, reporting values of 22 ppm, 23 ppm, 21 ppm, 20 ppm, 19 ppm and 17 ppm for WPPOB10, WPPOB20, WPPOB30, WPPOB40 and WPPOB100 respectively, compared to 20 % EGR percentage flow rates with 77 ppm, 68 ppm, 52 ppm, 46 ppm, 44 ppm and 40 ppm respectively.

Although the application of EGR % flow rate reduces the amount of UHC emissions remitted by the applied test fuels across the board, CD fuel produced more UHC emissions from the test engine compared to all the WPPO blends tested. Figure 10 shows that at EGR flow rates of 5 %, 10 %, 15 %, 20 %, 25 % and 30 %, CD UHC emissions were 43 ppm, 57 ppm, 70 ppm, 82 ppm and 85 ppm respectively, compared to WPPOB10 whose values were 23 ppm, 35 ppm, 40 ppm, 48 ppm, 50 ppm, and 52 ppm respectively.

Therefore, the application of EGR % flow rate increased UHC emissions as observed from the results and values presented and obtained in Figure 10, with CD fuel producing the highest UHC emission values compared to all the test fuel blends of WPPOB10, WPPOB20, WPPOB30, WPPOB40 and WPPOB100.

Nitrogen Oxide (NO_x) Emissions

Figure 11 shows variations of NO_x emissions (ppm) and engine loads with different blends of WPPO and CD fuel with EGR % flow rate application.

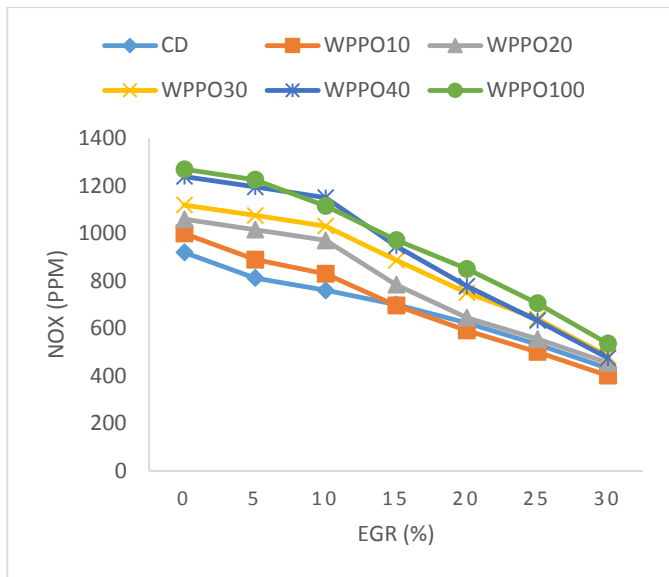


Figure 11. Variations of NO_x emissions (ppm) versus EGR % flow rate

NO_x emission formation is highly dependent on in-cylinder temperature, the concentration of oxygen, and the residence time the fuel-air mixture spends in the combustion chamber during the pre-mixing phase [41]. All the fuels tested indicated a drop in the NO_x emissions with an increase in the application of EGR % flow rate, at all engine load conditions. Figure 11 shows this was due to the rise in the total heat capacity of the working gases that increased with increasing EGR % flow rate, thus concurring with the studies and findings of [42], [43] and [44].

The NO_x emissions value for the CD in Figure 11 at full load was 920 ppm with application of EGR % flow rate, while WPPOB100 was 1270 ppm, compared to the reduced values with application of EGR % flow rate of 30 % in Figure 11, where CD NO_x emissions decreased to 432 ppm compared to 536 ppm before application of EGR % flow rate.

Figure 12 shows variations of NO_x emissions (ppm) under varying engine load with different blends of WPPO and CD test fuel without EGR % flow rate application.

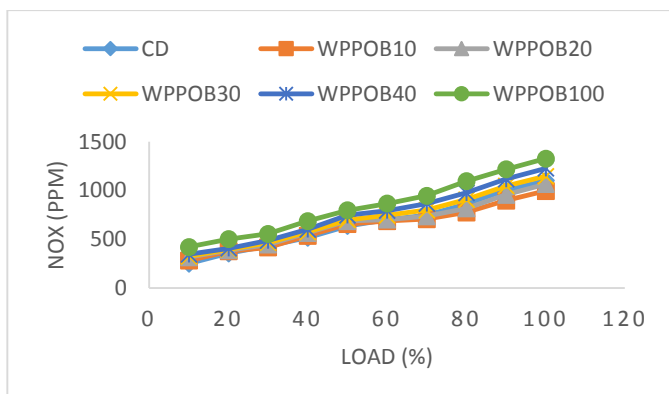


Figure 12. Variations of NO_x emissions (ppm) versus varying engine load % without application of EGR flow rate

During study it was observed that at engine part load, as shown in Figure 12, the values for NO_x emissions for all the fuels were lower compared to the values at full load engine conditions. The NO_x emissions for CD at engine part load (50 %) was 635 ppm compared to full load at 1100 ppm, whereas the value for WPPOB100 at engine part load (50 %) was 850 ppm compared to 1250 ppm at full engine load. This seems to indicate a concurrence that at part engine load (50 %) the values of NO_x emissions emitted by all the blends of WPPO except WPPO100 were lower compared to the values at full engine load conditions.

Carbon Monoxide (CO) Emission

Figure 13 shows CO emissions % variations versus varying engine load with different fuel blends of WPPO and CD test fuel with EGR % flow rate application.

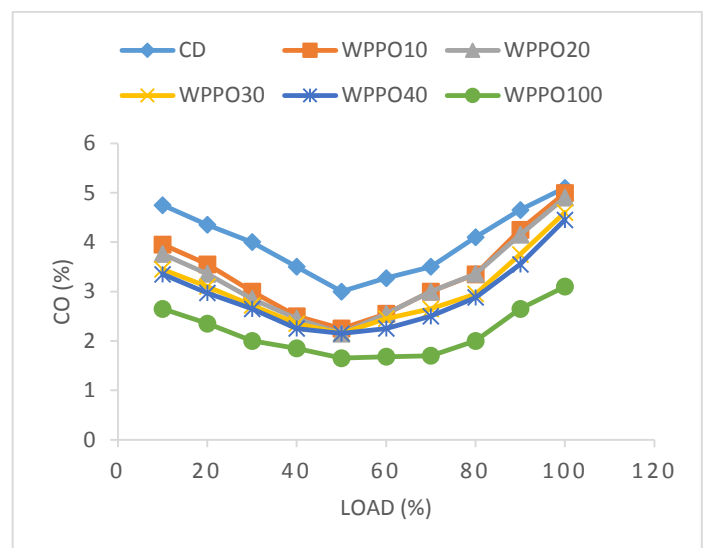


Figure 13. Carbon monoxide (CO) emissions % versus varying engine load

CO is a toxic gas that requires substantial control to acceptable levels. It is caused by poor combustion of hydrocarbon fuels as a result of dependency on the air-fuel ratio relative to the stoichiometric proportions [42].

For all the test fuels the amount of CO emissions seemed to decrease at lower engine loads up to part load percentages or intermediate loads of (50 %), after which the CO emissions continued to increase significantly and marginally as in Figure 13. At 0 % engine load the value of conventional diesel was 0.051 % compared to 50 % engine load when the value was reduced to 0.03 % by volume. However, as the engine load increased from 50 % there was a significant continuous and marginal increase in the percentage of carbon emissions by volume across all the test fuels irrespective of the EGR % flow rate. For example, at 80 % engine load the value for WPPOB100 was 0.02 % up from 0.0165 % by volume. The other WPPO biodiesel blends also showed a similar trend and concurrency. WPPOB20 and WPPO30 test fuels at 50 % engine load condition had values of 2.25 % and 2.15 %

compared to 3.36 % and 2.95 % respectively at 80 % engine load.

Figure 14 shows the variation of CO emissions with EGR % flow rate application under different blends of WPPO and CD.

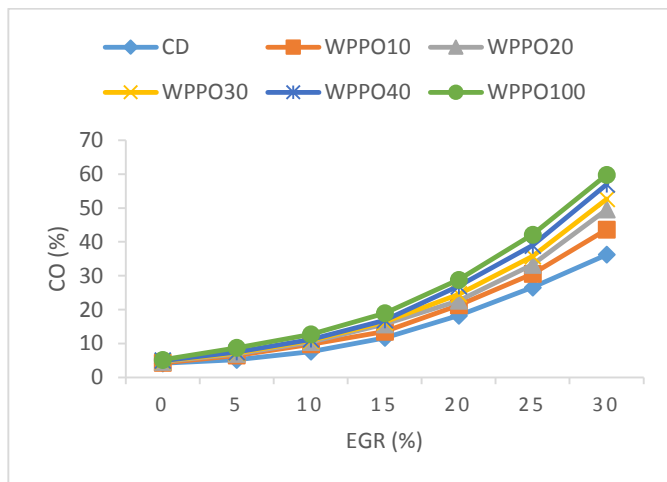


Figure 14. Carbon monoxide (CO) versus EGR % flow rate application

As shown in Figure 14, the WPPO blends are observed to produce a continuous increase in smoke emissions to almost double the values with the application of EGR % flow rate as in Figure 14. For example, at 10 % EGR flow rate, CO emission values were 9.79 %, 10.46 %, 10.91 %, 11.25 % and 12.75 % for WPPO10, WPPO20, WPPO30, WPPO40 and WPPO100 respectively. CD reported the lowest carbon emissions with the application of EGR % flow rate with a value of 7.65 %.

There was also a correlation between the blend ratio and EGR % flow rate on the amount of CO emissions produced. During experimentation it was observed that as the blend ratio increased the CO emissions increased as the EGR % flow rate increased as seen in Figure 10. At 20 % EGR flow rate CO emission values were 18.25 %, 21.35 %, 22.65 %, 24.55 %, 26.95 % and 28.85 % respectively for CD, WPPO10, WPPO20, WPPO30, WPPO40 and WPPO100. However, WPPO30 reported values of 4.85 %, 7.28 %, 10.91 %, 16.37 %, 24.55 %, 35.75 % and 52.69 % as the EGR flow rate increased from 0 % to 30 % respectively. This may be due to the effects of EGR % flow rate application and for dilution, thermal and chemical reasons some of the oxygen in the inlet charge was replaced with recirculated exhaust gas which caused incomplete combustion.

Carbon Dioxide (CO₂) Emissions

Figure 15 shows the CO₂ % variations under varying engine load with different blends of WPPO and CD test fuels.

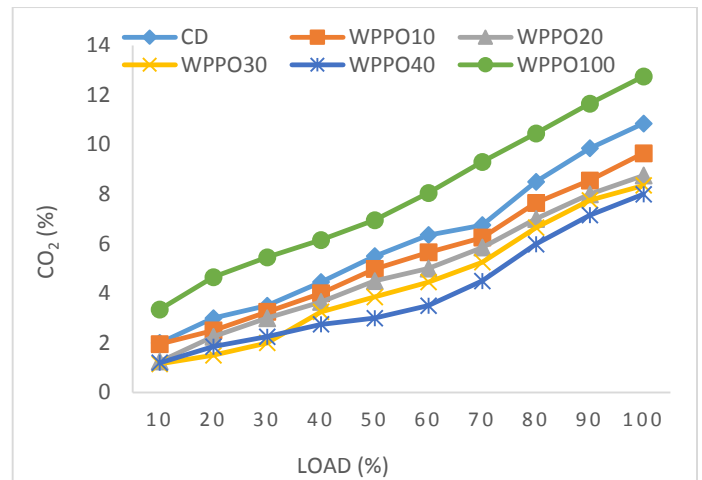


Figure 15. Variation of carbon dioxide (CO₂) % emissions versus engine Load %, with different types of fuel blends of WPPO and CD

CO₂ is the principal composition of EGR gases, and is a core indicator of the quality of combustion and the temperature [6] of combustion within the combustion chamber. CO₂ gas has a higher heat capacity which makes it act like a thermal heat sink especially during the combustion process, making it possible to reduce peak cylinder temperatures, hence is of particular importance in the process leading to the reduction in NO_x emissions.

Without EGR % flow rate and at lower engine loads, the value of CO₂ was considerably high for all the test fuels used. For example, at 20 % engine load WPPOB100 had the highest CO₂ emission value of 4.65 % compared to the other test fuels used, namely CD, WPPO10, WPPO20, WPPO30 and WPPO40 with 3%, 2.50 %, 1.5 %, 1.85 % respectively, as shown in Figure 15.

However, it can also be observed from Figure 15 that the amount of CO₂ increased with an increase in the engine load. As the engine load increased to 40 % the value of WPPOB40 was 2.75 % compared to WPPOB30 at 3.25 %, while at 70 % engine load the values 4.5 % and 5.25 % respectively. This leads us to the observation that as the engine load is increased with an increase in the blend ratios, lower ratio blends are observed to emit more CO₂ compared to higher ratio blends except blend WPPOB100 which released more CO₂ than any test fuel as mentioned earlier. At full engine load the value of CO₂ emissions were at their highest values across all the test fuels. The values were 12.75 %, 10.85 %, 9.65 %, 8.75 %, 8.35 % and 8 % for WPPOB100, CD, WPPOB10, WPPOB20, WPPOB30 and WPPOB40 respectively.

Figure 16 shows CO₂ % variations with different blends of WPPO and conventional diesel test fuel under engine load, with application of EGR % flow rate.

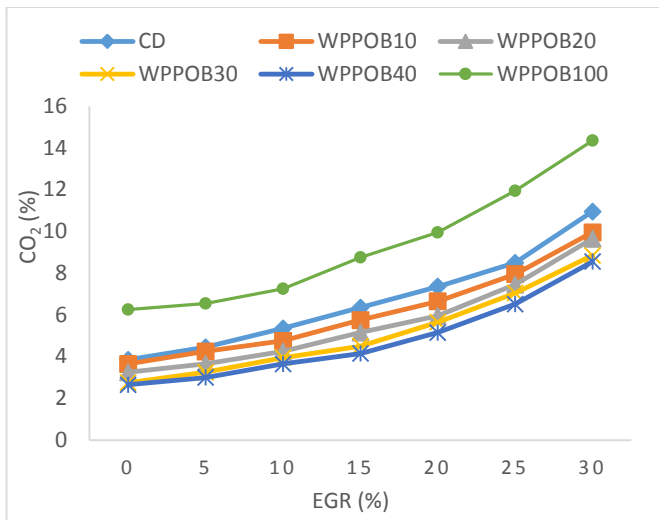


Figure 16. Variations of carbon dioxide (CO₂) % versus EGR % flow rate, with different types of WPPO fuel blends and CD

The application of EGR % flow rate increased the CO₂ emissions exponentially by almost doubling the values as can be seen in Figure 16. For example, at 10 % EGR flow rate the value of CD was 5.35 % compared to WPOB100 at 7.25 %, WPOB10 was at 4.75 %, WPOB20 at 4.25 %, WPOB30 at 3.95 %, and WPOB40 at 3.65 % respectively. These results reinforce the observation that CO₂ emissions with the application of EGR % flow rate have a correlation with blending i.e., the lower the blend ratio, the higher the emission values and vice versa. The values for 30 % EGR flow rate for all the test fuels contained high emissions for CO₂, for example CD was 10.95 %, WPOB10 9.95 %, WPOB20 9.65 %, WPOB30 8.85 %, and WPOB100 had the highest value of 14.35 %.

Smoke Emissions (Opacity)

This can be defined as the solid hydrocarbon soot particles that are found in exhaust system gases [45] and are directly linked to smoke emissions formation. For all the blends of WPPO there was a noted increase in the level of smoke emissions, although the levels and values were considerably lower compared to CD.

Figure 17 shows smoke emissions or opacity % variations at full engine load, with different blends of WPPO and CD under the effect of EGR % flow rate application.

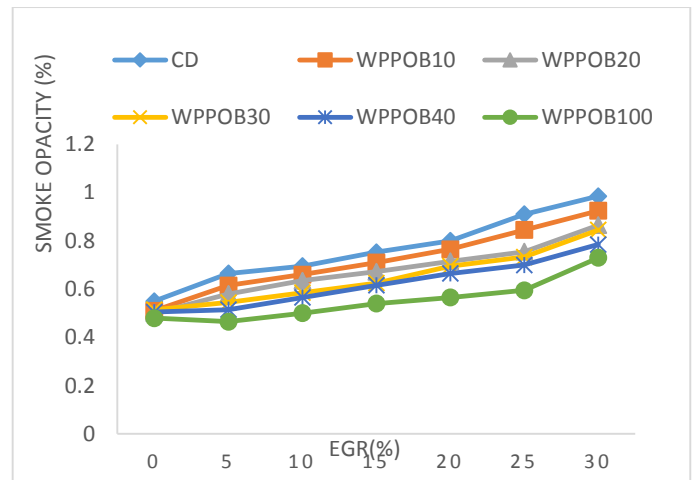


Figure 17. Variation of smoke emissions or opacity % versus EGR % flow rate, with different WPPO blends and CD

The steady increase in smoke emissions can be explained by the fact that WPPO blends of fuel have a high kinematic of viscosity compared to CD fuel, and they have low volatility values. Other possible explanations for this phenomenon are the poor injection and spray characteristics observed for WPPO blends of fuels compared to those of CD fuel which has better spray qualities. Another likely cause is associated with the high aromatic compounds found in most WPPO blends of fuel compared to CD fuel.

The application of EGR % flow rate showed that there was a significant increase in the values of smoke emissions and particulate matter emissions across all the test fuels. Smoke emissions with WPOB10 blend were 7.2 % lower compared to CD at 0 % EGR flow rate, with CD being 11.5 % higher than WPOB100 blend fuel at 30 % EGR flow rate. This result seems to concur with the study findings of [46].

The WPOB10 blend used in this study emitted the highest levels of smoke emissions of the blended fuels followed by WPOB100. However, it should be mentioned here that as the blend ratio and the EGR % flow rate increased there was a steady increase in the smoke emissions across all the test fuels compared to when the EGR % flow rate was at 0 %.

CONCLUSION

- As the percentage of the blends of WPPO increased there was a marked decrease in the engine BP of the blended fuels compared to CD. This is true considering that the energy content (Table 2) for the WPPO test fuel was lower compared to the CD test fuel.
- Peak power produced using WPPO biodiesel blends failed to match the peak power produced by CD, being in the region of 5% to 8% less compared to the peak power produced from the CD test fuel.
- Data presented in this work provides more reasons to support the widespread use of WPPO as an alternative fuel for all types of compression ignition engines with

or without modifications to the engines, especially when blends of WPOB10 and WPOB20 are used because in this study their peak BP and BSFC values were identical to CD.

- Results (Figure 12) indicate that less NO_x emissions occurred during part and intermediate engine load for the WPO test fuels and CD test fuel compared to full engine load.
- As the percentage ratio of the biodiesel WPO increased there was a significant increase in the BSFC (Figure 5) for the blends of WPO compared to the BSFC values of CD.
- An interesting observation during this experiment was that as the blends ratio increased there was a reduction in the percentage amount of CO emissions released by the test engine (Figure 13). This can be attributed to a higher oxygen content in WPO blended fuels compared to CD, aiding in complete combustion.
- The values of CO emission by WPOB10 and WPOB20 were observed to be close with minimal differences in terms of their volume percentage emissions of CO produced by the test engine (Figure 13).
- For all the test fuels, it was observed that at low engine loads from 10 % to 40 % there was a decrease in the amount of CO₂ emissions (Figure 14). However, there was a significant continuous and marginal increase in the percentage of CO₂ emissions by volume as the load increased to 50 % across all the test fuels irrespective of the EGR % flow rate.
- There was a steady increase in smoke emissions for all the blends of WPO with or without EGR % flow rate application, with test fuel blend WPOB10 producing the highest values of smoke emissions followed by the WPOB100 test fuel blend (Figure 16).
- There was a steady increase in smoke emissions due to the WPO blends of fuel having a high kinematic viscosity compared to the CD test fuel, in addition to having the low volatility. Other possible explanations for this phenomenon could be the poor injection and spray characteristics observed with WPO blends of fuels compared to CD which offers better spray qualities. Another likely cause is the high level of aromatic compounds found in most WPO blends of fuel compared to CD.
- The NO_x emission for CD at engine part load (50 %) was 635 ppm compared to full load at 1100 ppm, whereas the value for WPOB100 at engine part load (50 %) was 850 ppm compared to 1250 ppm at full engine load. This seems to indicate a concurrence that at part engine load (50 %) the values of NO_x emissions emitted by all the blends of WPO except WPO100 were lower compared to the values at full engine load conditions.

ACKNOWLEDGEMENT

First and foremost, to the good Lord for His enabling mercies, to my supervisor Prof F. L. Inambao for his tireless effort to

mould me, to my brothers D.K. Marwa, Dr J.M. Marwa and F.S. Marwa for their moral, financial, visionary leadership and support. Lastly to the UKZN and staff fraternity for the suitable environment, especially the LAN manager Shaun, the lab technicians and my fellow post-graduate students, who enabled me to complete this work.

REFERENCES

- [1] V. K. Kaimal and P. Vijayabalan, "A detailed study of combustion characteristics of a DI diesel engine using waste plastic oil and its blends," *Energy conversion and Management*, vol. 105, pp. 951-956, 2015.
- [2] İ. A. Reşitoğlu, K. Altinişik, and A. Keskin, "The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems," *Clean Technologies and Environmental Policy*, vol. 17, pp. 15-27, 2015.
- [3] B. R. Kumar and S. Saravanan, "Use of higher alcohol biofuels in diesel engines: A review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 84-115, 2016.
- [4] S. Kumar, R. Prakash, S. Murugan, and R. Singh, "Performance and emission analysis of blends of waste plastic oil obtained by catalytic pyrolysis of waste HDPE with diesel in a CI engine," *Energy conversion and management*, vol. 74, pp. 323-331, 2013.
- [5] D. Damodharan, A. P. Sathiyagnanam, B. R. Kumar, and K. C. Ganesh, "Cleaner emissions from a DI diesel engine fueled with waste plastic oil derived from municipal solid waste under the influence of n-pentanol addition, cold EGR, and injection timing," *Environmental Science and Pollution Research*, pp. 1-15, 2018.
- [6] K. Muralidharan, D. Vasudevan, and K. Sheeba, "Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine," *Energy*, vol. 36, pp. 5385-5393, 2011.
- [7] H. Yamada, K. Misawa, D. Suzuki, K. Tanaka, J. Matsumoto, M. Fujii, *et al.*, "Detailed analysis of diesel vehicle exhaust emissions: Nitrogen oxides, hydrocarbons and particulate size distributions," *Proceedings of the Combustion Institute*, vol. 33, pp. 2895-2902, 2011.
- [8] Department of Environmental Affairs, "National Waste Management Strategy," *Department of Environmental Affairs, Pretoria*, 2012.
- [9] A. Azad, M. Rasul, M. Khan, S. C. Sharma, and M. Bhuiya, "Recent development of biodiesel combustion strategies and modelling for compression ignition engines," *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 1068-1086, 2016.
- [10] C. T. Bowman, "Control of combustion-generated nitrogen oxide emissions: technology driven by

- regulation," in *Symposium (International) on Combustion*, 1992, pp. 859-878.
- [11] V. Mangesh and C. Thamocharan, "Evaluation of Engine Performance, Emissions, of a Twin Cylinder Diesel Engine Fuelled with Waste Plastic Pyrolysis Oil, Ethanol and Diesel Blends with Cetane Additive AC2010A," 2015.
- [12] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," *Science advances*, vol. 3, p. e1700782, 2017.
- [13] S. Kumar, A. K. Panda, and R. Singh, "A review on tertiary recycling of high-density polyethylene to fuel," *Resources, Conservation and Recycling*, vol. 55, pp. 893-910, 2011.
- [14] I. Kalargaris, G. Tian, and S. Gu, "Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil," *Fuel Processing Technology*, vol. 157, pp. 108-115, 2017.
- [15] C. Wongkhorsub and N. Chindaprasert, "A comparison of the use of pyrolysis oils in diesel engine," *Energy and Power Engineering*, vol. 5, p. 350, 2013.
- [16] D. Kim, S. Shin, S. Sohn, J. Choi, and B. Ban, "Waste plastics as supplemental fuel in the blast furnace process: improving combustion efficiencies," *Journal of hazardous materials*, vol. 94, pp. 213-222, 2002.
- [17] S. D. A. Sharuddin, F. Abnisa, W. M. A. W. Daud, and M. K. Aroua, "A review on pyrolysis of plastic wastes," *Energy conversion and management*, vol. 115, pp. 308-326, 2016.
- [18] C. Güngör, H. Serin, M. Özcanlı, S. Serin, and K. Aydın, "Engine performance and emission characteristics of plastic oil produced from waste polyethylene and its blends with diesel fuel," *International journal of green energy*, vol. 12, pp. 98-105, 2015.
- [19] J. Pratoomyod and K. Laohalidanond, "Performance and emission evaluation of blends of diesel fuel with waste plastic oil in a diesel engine," *Carbon*, vol. 79, pp. 75-99, 2013.
- [20] M. Mani, G. Nagarajan, and S. Sampath, "Characterisation and effect of using waste plastic oil and diesel fuel blends in compression ignition engine," *Energy*, vol. 36, pp. 212-219, 2011.
- [21] V. Guruprakash, N. Harivignesh, G. Karthick, and N. Bose, "Thermal barrier coating on IC engine cylinder liner," *Archives of Materials Science*, vol. 38, p. 38, 2016.
- [22] S. Saravanan, "Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed DI diesel engine fueled with pentanol/diesel blends," *Fuel*, vol. 160, pp. 217-226, 2015.
- [23] B. R. Kumar and S. Saravanan, "Effects of iso-butanol/diesel and n-pentanol/diesel blends on performance and emissions of a DI diesel engine under premixed LTC (low temperature combustion) mode," *Fuel*, vol. 170, pp. 49-59, 2016.
- [24] L. Wei, C. Cheung, and Z. Huang, "Effect of n-pentanol addition on the combustion, performance and emission characteristics of a direct-injection diesel engine," *Energy*, vol. 70, pp. 172-180, 2014.
- [25] J. Calder, M. M. Roy, and W. Wang, "Performance and Emissions of a Diesel Engine Fueled by Biodiesel-Diesel Blends with Recycled Expanded Polystyrene and Fuel Stabilizing Additive," *Energy*, 2018.
- [26] S. Gnanasekaran, N. Saravanan, and M. Ilangkumaran, "Influence of injection timing on performance, emission and combustion characteristics of a DI diesel engine running on fish oil biodiesel," *Energy*, vol. 116, pp. 1218-1229, 2016.
- [27] L. Li, J. Wang, Z. Wang, and J. Xiao, "Combustion and emission characteristics of diesel engine fueled with diesel/biodiesel/pentanol fuel blends," *Fuel*, vol. 156, pp. 211-218, 2015.
- [28] J. Devaraj, Y. Robinson, and P. Ganapathi, "Experimental investigation of performance, emission and combustion characteristics of waste plastic pyrolysis oil blended with diethyl ether used as fuel for diesel engine," *Energy*, vol. 85, pp. 304-309, 2015.
- [29] S. Hariharan, S. Murugan, and G. Nagarajan, "Effect of diethyl ether on Tyre pyrolysis oil fueled diesel engine," *Fuel*, vol. 104, pp. 109-115, 2013.
- [30] I. Kalargaris, G. Tian, and S. Gu, "The utilisation of oils produced from plastic waste at different pyrolysis temperatures in a DI diesel engine," *Energy*, vol. 131, pp. 179-185, 2017.
- [31] A. Sharma and S. Murugan, "Combustion, performance and emission characteristics of a DI diesel engine fuelled with non-petroleum fuel: a study on the role of fuel injection timing," *Journal of the Energy Institute*, vol. 88, pp. 364-375, 2015.
- [32] A. K. Wamankar and S. Murugan, "Effect of injection timing on a DI diesel engine fuelled with a synthetic fuel blend," *Journal of the Energy Institute*, vol. 88, pp. 406-413, 2015.
- [33] P. Senthilkumar and G. Sankaranarayanan, "Production of waste polyethylene bags in to oil and studies performance, emission and combustion characteristics in di diesel engine," *International journal of humanities, arts, medicine and science*, vol. 3, pp. 149-158, 2015.
- [34] M. Hawi, R. Kiplimo, and H. Ndiritu, "Effect of exhaust gas recirculation on performance and emission characteristics of a diesel-piloted biogas

- engine," *Smart Grid and Renewable Energy*, vol. 6, p. 49, 2015.
- [35] M. Paul Daniel, K. V. Kumar, B. Durga Prasad, and R. K. Puli, "Performance and emission characteristics of diesel engine operated on plastic pyrolysis oil with exhaust gas recirculation," *International Journal of Ambient Energy*, vol. 38, pp. 295-299, 2017.
- [36] D. Jagadish, P. R. Kumar, and K. Madhu Murthy, "Performance characteristics of a diesel engine operated on biodiesel with exhaust gas recirculation," *International Journal of Advanced Engineering Technolog*, vol. 2, pp. 202-208, 2011.
- [37] M. H. M. Yasin, R. Mamat, A. F. Yusop, D. M. N. D. Idris, T. Yusaf, M. Rasul, *et al.*, "Study of a diesel engine performance with exhaust gas recirculation (EGR) system fuelled with palm biodiesel," *Energy Procedia*, vol. 110, pp. 26-31, 2017.
- [38] P. N. Krishnan and D. Vasudevan, "Performance, combustion and emission characteristics of variable compression ratio engine fuelled with biodiesel," *International Journal of ChemTech Research*, vol. 7, pp. 234-245, 2015.
- [39] S. Maroa, Samwel and F. Inambao, "The Effects of Exhaust Gas Recirculation on the Performance and Emission Characteristics of a Diesel Engine—A Critical Review," *International Journal of Applied Engineering Research*, vol. 12, pp. 13677-13689, 2017.
- [40] A. Sharma and S. Murugan, "Potential for using a tyre pyrolysis oil-biodiesel blend in a diesel engine at different compression ratios," *Energy Conversion and Management*, vol. 93, pp. 289-297, 2015.
- [41] J. B. Heywood, "Internal combustion engine fundamentals," 2012.
- [42] M. Mani, G. Nagarajan, and S. Sampath, "An experimental investigation on a DI diesel engine using waste plastic oil with exhaust gas recirculation," *Fuel*, vol. 89, pp. 1826-1832, 2010.
- [43] M. Ghazikhani, M. E. Feyz, and A. Joharchi, "Experimental investigation of the exhaust gas recirculation effects on irreversibility and brake specific fuel consumption of indirect injection diesel engines," *Applied Thermal Engineering*, vol. 30, pp. 1711-1718, 2010.
- [44] K. I. Abaas, "Effect of Exhaust Gas Recirculation (EGR) on the Performance Characteristics of a Direct Injection Multi Cylinders Diesel Engine," *Tikrit Journal of Engineering Science (TJES)*, vol. 23, pp. 32-39, 2016.
- [45] H. Venkatesan, S. Sivamani, K. Bhutoria, and H. H. Vora, "Assessment of waste plastic oil blends on performance, combustion and emission parameters in direct injection compression ignition engine," *International Journal of Ambient Energy*, pp. 1-9, 2017.
- [46] P. Bridjesh, P. Periyasamy, A. V. K. Chaitanya, and N. K. Geetha, "MEA and DEE as additives on diesel engine using waste plastic oil diesel blends," *Sustainable Environment Research*, 2018.