THE INFLUENCE OF CETANE NUMBER AND OXYGEN CONTENT IN THE PERFORMANCE AND EMISSIONS CHARACTERISTICS OF A DIESEL ENGINE USING BIODIESEL BLENDS

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ABSTRACT

Waste plastic pyrolysis oil (WPPO) and ethanol are attractive renewable energy sources, as ethanol has a high content of oxygen. However, for this particular study, direct blending of conventional diesel, WPPO, ethanol and 2-ethyl hexyl nitrate (EHN) was attempted. The purpose was, firstly, to improve the combustion, ignition quality, performance and emission characteristics of the WPPO blends. Secondly, EHN has the potential to reduce emissions of CO, CO₂, UHC, NOₓ and PM. Thirdly, ethanol improves viscosity and miscibility of biodiesel blends, besides increasing the oxygen content of WPPO. Five mixing ratios were used in the following order, 50/WPPO25/E25, 60/WPPO20/E20, 70/WPPO15/E15, 80/WPPO10/E10 and 90/WPPO5/E5 for conventional diesel (CD), WPPO and ethanol respectively. However, for EHN the mixing ratio was determined by the total quantity of blended fuel and put at 0.01 %. Complete miscibility was observed with no phase separation allowed from the blended mixtures throughout the experiment. Performance and emission characteristics of a stationary single cylinder water-cooled diesel power generator were evaluated. The results obtained were compared carefully to ASTM standards and discussed using tables and graph figure curves. The conclusion was that ethanol and EHN can be used in diesel engine power generators as an alternative fuel to help improve cetane numbers and to increase the oxygen content without or with modification with WPPO blends. This is due to the densities 792 kg/m³, 963 kg/m³, 825 kg/m³ for WPPO, ethanol and EHN respectively, which are close to CD fuel at 845 kg/m³. The addition of EHN, reduced emissions and improved engine performance so that it equalled that of CD fuel.

Key words: 2-ethyl hexyl nitrate, Ethanol, High Content of Oxygen, Ignition Quality, Waste Plastic Pyrolysis Oil, Phase Separation.

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ABBREVIATIONS

ASTM  America Standard of Testing and Measurements  
BSFC  Brake Specific Fuel Consumption  
BTE  Brake Thermal Efficiency  
CD  Conventional Diesel  
CN  Cetane Number  
CO  Carbon Monoxide  
CO2  Carbon Dioxide  
EGT  Exhaust Gas Temperature  
EHN  2-Ethyhexyl Nitrate  
NOx  Oxides of Nitrogen  
PM  Particulate Matter  
UHC  Unburnt Hydrocarbon  
WPPO  Waste Plastic Pyrolysis Oil

1. INTRODUCTION

The increase of personal automobile transportation has significantly increased the demand for energy especially regarding primary sources of energy. Therefore, alternative solutions to meet this increasing energy demand associated with modern day development need to be found. Diesel engines, since their discovery by Rudolph Diesel in 1893, have proved superior, power efficient and good in fuel economy compared to gasoline engines. However, diesel engines emit high emission levels of oxides of nitrogen (NOx), carbon dioxide (CO2), unburnt hydrocarbons (UHC), particulate matter (PM) and smoke emissions. These emissions have been shown to affect human health and the health of the environment [1]. Diesel exhaust is now classified as carcinogenic [2] to humans with exposure linked to increased risk of lung cancer and cardiovascular diseases [3]. Diesel exhaust emissions are considered the primary source of ground level ozone [4], sick building syndrome [5], acid rain [6] and smog [7]. In addition, there are growing concerns over fossil fuel depletion, oil price fluctuations, and stringent emission regulation controls. Therefore, the importance of finding an alternative source of fuel energy with desirable characteristics similar to those of petroleum based fossil fuels cannot be overemphasized [8, 9].

Early developments in alternative fuel energy studies utilized food-based sources as alternatives to petroleum fuels. However due to poor food security in low middle income countries and developing countries this practice has faced opposition and arguments from all sectors and the organizations such as the United Nations Food and Agriculture Organization and the United Nations Human Rights Commission. The first-generation food-based biodiesels led to cultivation of large swaths of land for commercial purposes eventually supressing the edible food crop acreage which increased food insecurity which increased food prices and economic inflation [9].

There has been a recent increase in interest in higher level alcohols due to their high energy levels, higher cetane numbers, better blend stability, less hygroscopic tendencies, increased carbon chain length and improved ignition quality of the alcohol fuel molecules [10], compared to the lower alcohols ethanol and methanol. Alcohols are classified under oxygenated fuels with a hydroxyl (OH) group. The availability of oxygen inherent in their molecular structure during combustion reduces smoke emissions in diesel engines particularly during high engine loads as reported by [11]. The reduction in smoke emissions and opacity is linked to the oxygen content of the blends of diesel and alcohol [12]. Through research and collaboration with various biotechnology research groups there has been an improvement in the yield of higher level
alcohols through processing cellulose by means of modern fermentation processes such as using clostridium species [13], biosynthesis from glucose using genetically engineered microorganisms like Escherichia coli [14], cyanobacteria [15] and saccharomyces cerevisiae [16].

There are two reasons why ethanol can be considered a suitable additive to WPPO blends: firstly, because ethanol is produced from raw material of plant or plant waste origin, qualifying as an alternative renewable source of energy, and secondly because of its high oxygen content and thirdly its solubility in WPPO blends [17-21]. However, a number of studies have shown that increase in the ethanol fraction decreases the auto-ignition properties of diesel due to ethanol’s low propensity to auto-ignite as reported by [19, 22-30]. This finding shows a decrease in the cetane number (CN) value of the blends with diesel as the fraction of ethanol increases [22, 24, 27, 30].

There are a number of researchers who have used fuel additives in their work on WPPO biodiesel and other biodiesels [11, 31-49]. [50] studied how to reduce NO_{X} and PM emissions in a diesel engine. To achieve this aim they employed both ethanol and selective catalytic reduction over catalyst Ag/Al_{2}O_{3}, using blends of biodiesel-ethanol fuel (BE). These researchers reported increased UHC, carbon monoxide (CO) and PM emissions of 14 % due to the increase in the soluble organic fraction of PM emissions. However, they additionally reported the Bosch smoke number reduced by between 60 % to 80 % based on the European Stationary Cycle standard. The NO_{X} emissions were reduced by a significant margin of 73 %, thus leading them to conclude that a combination of BE and selective catalytic reduction catalyst arrangement could provide a good platform for NO_{X} and PM reduction and control.

[51] sought to determine cold flow features and characterization of ethanol-based biodiesel compared to diesel fuel. Their study presented the relationship of these fuels to torque, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and emission characteristics in diesel engines. As a result of their research work in the last decade, developed countries such as Europe and America have now made it mandatory for fuel manufacturers and distributors to add between 1 % to 5 % biofuel to most commercially available diesel fuels. In America, the renewable fuel standard program now requires blending of advanced biofuels with fossil fuel used in transportation in an increasing amount. The government target is to achieve an annual projection growth escalation of 36 billion gallons by the year 2022 [52].

Reduced CN fuel values are undesirable because of the tendency of low CN to prolong ignition delay. This causes increased engine peak cylinder combustion pressures [53, 54], increased engine combustion noise and wear, in addition to increased NO_{X} emissions. This impact of CN has been extensively studied and concluded by researchers such as [55-65].

Research on WPPO has shown that using the pyrolysis technique to extract liquid fuel from plastic waste material is a viable alternative to diesel fuel production and is sustainable. This is true especially when waste plastic oil is used with fuel additives [66]. Statistics show that as of 2016, only a paltry 9 % of waste plastic worldwide is being recycled with almost 80 % going to landfills to continue degrading the natural environment as plastics are non-biodegradable. This is a poor response and alarming as the gap between generation and recycling continues to increase, thus requiring bridging [67].

Plastic pyrolysis can be done using catalytic pyrolysis and other thermal processes. The catalytic method uses low levels of temperature to cause plastic degradation and decomposition compared to the thermal technique which requires very high temperature to produce high and greater liquid fuel. This has helped in recycling waste into energy and creating a circular economy. This is a development that has captivated and motivated a crop of researchers such as [68-70].

Plastics have a lot of stored potential energy of hydrocarbons inherent in their molecular structure. They are readily available as waste in municipal solid waste management sites where

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they are posing an environmental danger. Altering them through modern methods of decomposition, they can be converted to liquid fuels and used as biodiesels. Therefore, this work seeks utilization of development in fuels that are derived from renewable feedstock sources such as municipal solid waste disposed plastics. Through blending, this work intends to utilize waste by turning it into energy in line with other energy sustainability studies, by including ethanol to increase the oxygen content and 2-ethylhexyl nitrate which improves the cetane number and reduces emissions of CO, CO₂ and NOₓ. Additionally, this work provides and makes a strong case for alternative fuels to replace petroleum-based fossil fuels like diesel which is commonly used as the primary propulsion fuel in the transport industry, and to generate power from waste feedstock.

2. METHODOLOGY AND EXPERIMENTAL SET-UP

This experiment is making a case for blending of WPPO whose n-alkenes have 25 % less auto-ignition delay time compared to diesel fuel and whose n-alkenes are good for auto-ignition. The aromatics which affect PM emissions are very low in WPPO blends. According to [71] and [72], WPPO consists of iso-alkanes, n-alkanes and olefins in the region of 27 %, 25 %, and 9 % respectively with over 30 % of content being undefined due to complicated chemical bond structures. However, aromatic cyclo-alkanes (naphthalene) and others poor in auto-ignition were found to be 40 % of WPPO by [73]. Blending with ethanol was used in this experiment to improve the low pour point of WPPO so as to improve its cold starting characteristics. Secondly, blending was used to improve the fuel spray characteristics because ethanol is soluble and miscible in WPPO blends. Thirdly blending helped this experiment to improve the viscosity of WPPO biodiesel, thus aiding and improving its spray characteristics.

![Schematic diagram of the test engine set up rig](image)

**Figure 1.** Schematic diagram of the test engine set up rig

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

### 2.1. Engine Tests

The experiment was conducted using a naturally aspirated single-cylinder diesel engine power generator, water cooled, direct injection, Kirloskar TV1, in the Department of Mechanical Engineering Laboratory, University of KwaZulu-Natal in Durban, South Africa. The details of the engine and specifications are described in Table 1, while Figure 1 shows a schematic of the engine test setup.

**Table 1.** Experimental engine specifications
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| Parameters                  | Position value |
|-----------------------------|----------------|
| Ignition type               | 4 (Stroke)DICI |
| 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 Nm @ 1500   |
| Injection pressure          | 250 Bar        |

2.2. Physicochemical Property Analysis

WPPO by pyrolysis was obtained from a commercial plant whose production flow-chart is shown in Figure 3. Ethanol, conventional diesel and EHN were purchased from local outlets and blended using a homogenizer for 5 min at 3000 rpm. The properties of all samples were measured in the Department of Chemical Engineering Laboratory, University of KwaZulu-Natal in Durban, South Africa. Table 2 shows some important physicochemical properties of the fuels before blending. Table 3 shows the physicochemical properties of the blended fuel mixtures and their determined fuel properties after blending. Figure 2 is a photographic shot of the sample distillates of WPPO obtained from pyrolysis.

Figure 2. The distillate samples from the waste plastic pyrolysis oil samples

Table 2. Properties of diesel, WPPO and ethanol before blending and addition of EHN
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| PROPERTIES                | UNIT | CD   | WPPO | ETHANOL |
|---------------------------|------|------|------|---------|
| Density @ 20°C            | kg/M³| 845  | 825  | 792     |
| Visc. @ 40°C              | cSt  | 3.04 | 2.538| 1.05    |
| Cetane Number             | –    | 55   | –    | 8.5     |
| Flash Point a°C           | %    | 50   | 43   | 16      |
| Fire Point a°C            | %    | 56   | 45   | 53      |
| Carbon residue %          | %    | 22   | 0.015| –       |
| Sulphur content %         | %    | <0.028| 0.248| –       |
| Gross Calories kJ/kg      | %    | 46500| 43340| 29700   |
| Cetane index              | –    | 46   | 65   | –       |

Table 3. Properties of blended ratio mixtures of diesel, ethanol, WPPO with EHN

| Property                  | Unit       | CD 90/5/5 | 80/10/10 | 70/15/15 | 60/20/20 | 50/25/25 | STANDARD   |
|---------------------------|------------|-----------|----------|-----------|-----------|-----------|------------|
| Density Kg/M³             | 845        | 838.5     | 834      | 830       | 825       | 823       | ASTM D1298 |
| KViscosity @ 40°C         | 3.452      | 2.38      | 2.37     | 2.365     | 2.340     | 2.325     | ASTM D445  |
| Cetane Number             | 45         | 59        | 62       | 64        | 65        | 69        | ASTM D4737 |
| GCV kJ/kg                 | 44840      | 40125     | 39985    | 38700     | 36800     | 34500     | ASTM D4868 |
| Sulphur Content %         | <0.0124    | 0.0248    | 0.0249   | 0.0251    | 0.0253    | 0.0257    | ASTM D4294 |
| Oxygen %                  | 12.35      | 13.80     | 14.75    | 15.15     | 16.25     | 17.35     | ASTM D5622 |
| Carbon Residue %          | 74.85      | 75.35     | 76.40    | 77.55     | 78.25     | 79.65     | ASTM D7662 |
| Flash point a°C           | 56.5       | 38.5      | 37.55    | 37.35     | 37.15     | 36.85     | ASTM D93   |
| Hydrogen %                | 12.38      | 7.5       | 7.55     | 7.65      | 7.75      | 7.95      | ASTM D7171 |

Figure 3. Waste plastic pyrolysis oil processing plant flow chart

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.
3. RESULTS AND DISCUSSION

3.1. Brake Thermal Efficiency

The BTE variations with engine load are shown in Figure 4. The graphs show that as the load increased there was an increase in the BTE across all the test fuel blends of WPPO and for CD. At 50 % engine load the values for blends 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, 50/WPPO25/E25 and CD were 22 %, 21 %, 20 %, 18 %, 16.5 % and 22.5 % respectively. As the blend ratio and engine load increased, there was an increase in BTE across the blends of WPPO but a decrease in the BTE within the blends. At 25 % engine load 90/WPPO5/E5 had values of 14 %, 22 %, 26.5 % and 25 % compared to 70/WPPO15/E15 with 12.5 %, 20 %, 22.5 % and 23 % respectively.

The highest BTE value was reported for blend 90/WPPO5/E5 at 25 % engine load compared to any other blend of WPPO, ethanol and addition of EHN. Figure 5 shows values of 24.8 %, 23 %, 21 % and 19 % respectively for blends 80/WPPO10/E10,70/WPPO15/E15, 60/WPPO20/E20, 50/WPPO25/E25. However, blend 50/WPPO25/E25 reported the lowest values compared to the other blends. At 25 % engine load the BTE value was 9.5 % compared with full load at 19 %, this are the lowest values of BTE as shown in Figure 2 for all the blends tested.

![Figure 4. Brake thermal efficiency versus load](image-url)

3.2. Brake Specific Fuel Consumption

Figure 5 is the variation of BSFC with engine load. The BSFC compared to the engine load in Figure 5 shows that as the load increases there is an equal increase in the amount of fuel consumed by the test engine. The values obtained at full engine load for the blends of 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, 50/WPPO25/E25 and CD were 0.04 g/kW.h, 0.041 g/kW.h, 0.042 g/kW.h, 0.043 g/kW.h and 0.035 g/kW.h respectively.

At high engine loads the conversion of heat energy to mechanical energy increases with increase in combustion temperature, leading to increased BSFC for the biodiesel; this increase is proportional to the difference in their heating values which is identical to the findings of [74]. These blends of WPPO compare well to conventional diesel fuel and sometimes other biodiesel blends with comparable differences in heating values.
As the blend ratio increased there was a decrease in the BSFC across all the test fuels, although the values for all WPPO blends were slightly higher compared to the CD test fuel. The closeness of the values and the packed graph reveal a close resemblance and identical BSFC characteristics of WPPO, ethanol and EHN compared to CD fuel. For example, at 50 % engine load the blend of 80/WPPO10/E10 had a value of 0.043 g/kW.h compared to full engine load with 0.041 g/kW.h. This value is higher than CD test fuel with 0.04 g/kW.h at 50 % engine load and 0.035 g/kW.h at full engine load.

3.3. Exhaust Gas Temperature

The variation of exhaust gas temperature (EGT) and engine load is shown in Figure 6. The graph reveals that as the load increased the value of the EGT increased significantly especially for the blends. At 25 % engine load the blends 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, 50/WPPO25/E25 reported values of 165 °C, 195 °C, 226 °C and 256 °C respectively, compared to CD with 155 °C, 175 °C, 205 °C and 240 °C for all engine load conditions.

As the engine load increased from 25 % to full load (100 %) the graph curves tend toward unitary and are similar to the values of the CD test. Thus it can be concluded that the blends of WPPO, ethanol and fuel additives have almost identical temperature characteristics to those of the CD test fuel, especially as the engine load hits 75 % heading to 100 % (full load). This was attributed to the presence of ethanol which decreased ignition delay thus lowering the combustion temperature.
3.4. Carbon Monoxide

Figure 7 is a variation of CO with engine load. The graph reveals that as the engine load and the blend ratio increased through blends 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, and 50/WPPO25/E25, CO emissions decreased up to 75 % of engine load. Thereafter the blends reported a continuous increase as the engine load was approaching full load. At 25 % engine load the blends of 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, and 50/WPPO25/E25 reported values of 0.055 %, 0.0565 %, 0.06 %, 0.0615 % and 0.0625 % respectively.

However, as the load is increased to 75 % the values are 0.035 %, 0.0375 %, 0.0445 % and 0.0475 respectively. At full load all the test fuels showed increased CO emissions with blends 90/WPPO5/E5 and 80/WPPO10/E10 reporting the lowest emissions among the test blends across all the engine load conditions. At 50 % these two blends reported values of 0.0445 % and 0.0475 % compared to full load with 0.0425 % and 0.0465 % respectively. The increased CO emissions, though lower compared to diesel fuel, can be attributed to partial combustion [75] as the load increased and the presence of ethanol which shortened ignition delay, thus increasing CO emissions.

As the engine load and the blend ratio increased there was an increase in the carbon monoxide emission across all the engine loads within the blends and the CD test fuel. At 50 % engine load, the values of the blends and CD were 0.045 %, 0.0475 %, 0.0515 %, 0.0535 %, 0.0565 % and 0.05 % for 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, and 50/WPPO25/E25 and CD respectively. The above values obtained from Figure 4 suggest that there is a reduction of CO emissions across all test fuels irrespective of blend ratio and type of fuel except at high engine loads exceeding 75 % to full engine load. After this point there is a steady increase in the emissions of CO.

CO emissions are a direct result of poor oxidation of the hydrocarbon fuels in the combustion chamber, which is determined by the local fuel/air equivalence ratio. Compared to CD, all other biodiesels tested showed decreased CO emissions due to the high oxygen content in the test biodiesels and the addition of EHN which greatly increased the CN. This is identical to studies by [56, 76]. However, as the engine load increased from 75 % towards full load (100 %), there is an observed increase in CO emissions, despite the oxygen content of the biodiesel and increased CN of the blends of WPPO, ethanol and EHN. This disagreement in results is due to differences in CN for the different biodiesel test fuel blends used. The increment in CN as the blend ratio increased led to increase in fuel quantity burnt during diffusive combustion, hence CO emissions increased as the quality of combustion decreased.
3.5. Carbon Dioxide

Figure 8 is the variation of CO₂ with engine load. The graph shows that as the blend ratio and engine load increased, CO₂ emissions increased, but compared to CD their emission levels were still lower and almost identical. At 50 % engine load the values of CD, and the blends of 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, and 50/WPPO25/E25 were 3.58 %, 3.35 %, 2.95 %, 2.6 %, 2.55 % and 2.25 % respectively.

![Figure 8. Carbon dioxide versus load](https://ssrn.com/abstract=3452440)

Figure 8 also reveals from its graph plot that as the load increased there was a significant increase in the CO₂ emissions across all test fuels, although with lower values as the blend ratio increased. For example, CD fuel had values of 2 %, 3.85 %, 5.95 % and 8.95 % for engine loads of 25 %, 50 %, 75 % and 100 % compared to blend 80/WPPO10/E10 with 1.8 %, 2.95 %, 4.85 % and 8.55 % for the same loads. The blend with the lowest value of CO₂ emission was 50/WPPO25/E25 with values of 1.62 %, 2.25 %, 3.65 % and 7.35 % for engine loads of 25 %, 50 %, 75 % and 100 % respectively.

3.6. Unburnt Hydrocarbons

Figure 9 is a variation of UHC emission with engine load. As the engine load was increased the UHC emissions increased too. However, the increase was more significant when the engine load was moving from intermediate loads of 75 % to or approaching full load. For example, at 50 % engine load the values of blends 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15, 60/WPPO20/E20, 50/WPPO25/E25 were 22 ppm, 21 ppm, 20 ppm, 18 ppm and 15 ppm respectively compared to full load with 35 ppm, 34 ppm, 32 ppm, 29 ppm and 26 ppm respectively. This leads to the conclusion that at high engine loads the values of UHC emissions are significantly higher for all the blends of WPPO, ethanol and EHN, although comparatively lower than CD fuel.

The UHC emissions from the blends 90/WPPO5/E5 and 80/WPPO10/E10 had higher values although from the graph plot in Figure 9 it is evident that the values are still low compared to the values of the CD test fuel. However, the general trend reported by the graph in Figure 9 shows that as the blend ratio increased there was significant reduction in the UHC emissions, observed across all the test fuels irrespective of the engine load condition, for all the blends tested compared to CD fuel.
The higher hydrocarbon emissions may be due to hydrogen radicals in the diesel-ethanol-WPPO-EHN blends. High fractions of ethanol in blends 70/WPPO15/E15, 60/WPPO20/E20, and 50/WPPO25/E25 contributes to an increase in the emissions of UHC which is identical to the findings of [77] and [23] who observed it in SI engine cylinder walls, crevices and quenched cylinder walls, especially when richer air-alcohol mixtures were introduced.

3.7. Oxides of Nitrogen

The variation of engine load with NOX emissions is shown on Figure 10. The graph plot shows that as the engine load increased there was an increase in the NOX emissions irrespective of fuel, blend ratio or EHN. However, the value of NOX emissions from the blends 90/WPPO5/E5, 80/WPPO10/E10, 70/WPPO15/E15 reported lower values compared to CD fuel. For example, at 50 % the value of the blends were 385 ppm, 396 ppm and 415 ppm respectively, compared to CD fuel at 425 ppm.

Blends 60/WPPO20/E20 and 50/WPPO25/E25 had the highest NOX emissions compared to the other blends of 90/WPPO5/E5, 80/WPPO10/E10, and 70/WPPO15/E15 across all the engine load conditions tested. At 25 % engine load the two blends had values of 205 ppm and 200 ppm respectively. However, at full engine load the NOX emissions values increased to 925 ppm and 885 ppm compared to blend 90/WPPO5/E5 at the same load with 197 ppm and at full load 792 ppm.

From the graph plot in Figure 10 it is evident that as the blend ratio increased there was a direct increase in the emissions of NOX across all the blended test fuels. However, blend...
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90/WPPO5/E5 reported the lowest values of NO\textsubscript{X} emissions compared to all the other blends that were tested in this experiment.

The formation of NO\textsubscript{X} in biodiesel combustion strongly depends on the combustion temperatures and combustion zone oxygen concentration. With high blend ratios of 70/WPPO15/E15, 60/WPPO20/E20, and 50/WPPO25/E25, the combustion process is shortened, thus leading to failure to provide enough cooling effect to decrease peak combustion temperatures leading to increased NO\textsubscript{X}.

These findings seem to show that there is a correlation between the alcohol content in the fuel and peak flame temperatures, content of nitrogen, and oxygen availability [78]. Increased NO\textsubscript{X} emissions can be attributed to the presence of nitrogen from the CN improver ENH and other contaminants from the WPPO composition. Additionally it could be due to the generation of radicals of hydrocarbon through molecular unsaturation, being identical to the findings of [79, 80]. However, the NO\textsubscript{X} levels are still low which can be attributed to the high CN numbers of the tested biodiesels (Table 3), and the increased oxygen content as the CN and blend ratios increased. These findings are identical to the findings of [81].

4. CONCLUSIONS

- The BTE of blend 90/WPPO5/E5 showed values which were very close to the values of CD fuel values. This can be attributed to close density values and the gross calorific values of WPPO blends, which showed very small and marginal differences. This was apparent especially at lower blend ratios of all the mixtures and blends tested.

- The lower blend ratios 90/WPPO5/E5 and 80/WPPO10/E10 exhibited identical BSFC of conventional diesel test fuel compared to the other blends. These blends showed the lowest BSFC values compared to the other blends.

- There was a reduction of UHC emissions with the use of WPPO blends, ethanol and EHN, with a notable reduction in NO\textsubscript{X} emissions especially for the blend 90/WPPO5/E. This is a clear indication that this blend performed well when it is compared to CD.

- Although there was an increase in the emissions of CO, CO\textsubscript{2}, NO\textsubscript{X} and UHC for all the blends of WPPO, ethanol and EHN, there is a clear indication in all the graphs discussed in this work that the emission levels are very low compared to the emission levels of CD. This comparison is in relation to ASTM standards. However, when the overall values of emissions are compared to other emissions standards, the WPPO blend performed well on emission levels tested.

- During experimentation it was observed and reported that the blends of WPPO, ethanol and EHN had almost identical temperature characteristics to those of the CD test fuel especially as the engine load hits 75 % heading to 100 % (full load). This was attributed to the presence of ethanol which decreases ignition delay.

- It is evident that the presence of high oxygen enrichment was a contributing factor to the decreased CO emission for the tested biodiesels compared to CD fuel, although there was an increase of CO emissions as fuel CN and blend ratio increased. The reason for this may be the deterioration of the combustion characteristics especially as the CN increases and the blend and alcohol ratio increases. The biodiesels with extremely high CN in the tested fuel need further investigation as a fuel improver.

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