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OPTIMISATION OF ENGINE PERFORMANCE AND EMISSIONS FUELED BY BIODIESEL BLENDS

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Abstract

This study sought to find out the optimisation of engine performance and emissions fueled by biodiesel blends. Compression ignition(CI) engines are most widely used as a power source for many applications, such as automotive and agricultural purposes, as well as portable machines, because of their higher torque, power output, energy content per unit mass, and fuel cost. Unfortunately, CI engines use diesel fuel, which emits greenhouse gases (GHG) and pollutes the environment. Biodiesel has been the preferred alternative fuel due to its benefits of reducing GHG emissions and being used on engines with little or no modification. Biodiesel blends with diesel were introduced to mitigate its decreased engine performance. Unfortunately, it has been difficult to obtain the best blend mix ratios for optimal engine performance and emission since biodiesels are sourced from a variety of vegetable oils whose fuel properties and their interactions differ considerably, causing variation in their combustion processes. The study used non-dominated sorting genetic algorithm II (NSGA II) optimisation to establish the best biodiesel blend to optimise engine performance and emissions. In conclusion, the study found that specific biodiesel blends for various feedstocks (waste vegetable oil, canola, oleander, coconut, and sunflower) achieved the optimal balance between reducing harmful emissions and maintaining engine performance. This study suggests expanding the model's inputs to encompass more fuel properties, engine types, and real-world conditions to improve its applicability, efficiency, and reliability.

Key terms: Biodiesel blends, engine performance, exhaust emission, optimisations.

1.0 INTRODUCTION

The Compression ignition (CI) engines were designed to run optimally on diesel (Heywood, 1988) and have been dominantly used for a long time in heavy machinery, transportation, farm operations, and light industries as a result of high thermal efficiency and low fuel consumption (Zheng et al., 2009). Besides useful power, these engines emit considerable amounts of greenhouse gas (GHG) from their exhausts consisting mainly of nitrogen oxides (NOx), carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC) and particulate matter (PM) (Lindstad et al., 2017; Menga et al., 2022). GHG emissions have been emphasised in recent years because of their adverse effects on environmental pollution, global warming and human health risks (Burchart-Korol et al., 2019), and currently, environmental policies have placed stringent standards to control emission levels (Lindstad et al., 2017; Elumalai et al., 2021). To overcome these challenges, researchers have focused on numerous renewable energy options. In recent years, biodiesel has gained prominence as a potential major substitute alternative to diesel worldwide due to its similarity in their fuel properties (lower heating value, flash point, and cetane number) and its ability to reduce emissions of GHG (Aydin, 2020) while tapping into locally available resources. Biodiesel is a renewable, non-toxic fuel made of a long chain of fatty acid esters produced from triglycerides of vegetable oils or animal fats (Barnwal et al., 2005).

2.0 LITERATURE REVIEW

Engines running on biodiesels, unfortunately, have been associated with reduced engine performance (Singh et al., 2007). The reduced performance was attributed to biodiesel's lower heat value and higher viscosity compared with diesel. The lower heat value results in low brake power; in contrast, higher viscosity leads to poor atomisation, both leading to low engine efficiencies (Gupta et al., 2007). Biodiesel blended with diesel has been used as a trade-off to achieving reduced exhaust emissions and improved engine performance (Zheng et al., 2009). Unfortunately, earlier studies have reported variability of test results in engine performances and emission characteristics for blends with similar fuel parameters (Lapuerta et al., 2008). These differences in reported results are attributed to the fact that biodiesel is produced from feedstock of different vegetable oils, which have different fuel properties affecting combustion processes and mechanisms differently (Aydin, 2020). Fuel properties like density, kinematic viscosity, and calorific value significantly affect engine performance and emissions (Giakoumis, 2013). For example, the engine thermal efficiency strongly depended on the biodiesel feedstock, with sources high in unsaturated fats generally showing better performance. In conclusion, most of the research works proved that the lower blends of biodiesel feedstocks exhibited lower exhaust emissions with improved performance in CI engines without any engine modification (Lapuerta et al., 2008). Thus, it is a challenging task for researchers to locate the best biodiesel-diesel blend ratios for the different feedstocks that target simultaneous mitigation of engine emissions with improved performance. Thus, optimisation of the performance and emission for engines running on biodiesel blends is paramount (Gupta et al., 2007) to obtain the best mix ratios for the different biodiesel (Khan et al., 2024) developed models and optimised engine performance successfully using the non-dominating Sorting Genetic Algorithm (NSGA-II). The mathematical models have also been used to simulate the engine performance for optimal operating conditions (Hoang et al., 2023). In the work of Martinez-Morales et al. (2013), artificial neural networks were used for multi-objective optimisation of a gasoline engine evaluated in the framework of the NSGA-II algorithm. In this research, the engine performances and emissions were optimised using the multi-objective using NSGA II.

3.0 MATERIALS AND METHODS

The waste vegetable oil (WVO), coconut, canola, sunflower, Oleander biodiesels, and diesel for experiments were purchased from petroleum outlets in Thika town, Kiambu County in Kenya. The biodiesels were blended with diesel at different ratios based on volumes measured using a beaker and burette and stirred by an electric blender for 3 minutes.

Fuel Properties

The biodiesel blends B10 (10% biodiesel, 90% diesel), B15, B20, B25, and B30 for WVO, Coconut, canola, sunflower, and oleander prepared were sampled. The fuel properties for density, kinematic viscosity, and lower heating value of the biodiesel blends were determined for testing using American Standard Tests and Measures (ASTM) procedures (Lapuerta et al., 2008). The ASTM D1298 (ASTM International, 2018b) procedure was used to measure densities. The kinematic viscosity of the fuels was determined using a redwood viscometer as specified in the test method ASTM D445-18 (ASTM International, 2018c). The lower heating values (LHV) of the test fuels were determined using a Nenken -type adiabatic bomb calorimeter, Model 1013-B, following the ASTM D2015-18 standard test method (ASTM International, 2018).

Engine Performance and Emissions Test

Engine tests were conducted to validate performance and emission mathematical models developed by Kibiwot et al. (2024). The test used a single-cylinder, four-stroke cycle Variable Compression Ratio (VCR) Apex 240PE engine test rig connected to an eddy current dynamometer. The test rig had a stand-alone panel equipped with a computer-assisted data acquisition system. The variation of the brake load and speed on the eddy current dynamometer were adjusted using a control knob on the dashboard. The stand-alone panel box consisting of an air box, fuel tanks, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, dashboard load/speed knob, hardware/software interface switch, rotameters to measure the water flow for the cooling engine and calorimeter and the indicators fitted in the control panel measure the speed and load readings. All the data were read, displayed, and stored using a computer with an installed LabVIEW-based engine performance analysis software package “Engine soft” version 2.4, interfaced with the signals from the engine sensors. The data collected and recorded by the engine soft included engine speed, fuel flow rate, air flow rate, brake thermal efficiency and specific fuel consumption. Horiba PG-250 gas analyser mounted on the exhaust pipe for capturing carbon monoxide (CO) and nitrogen oxide (NOx) emissions data. The setup is shown in Figure 1.

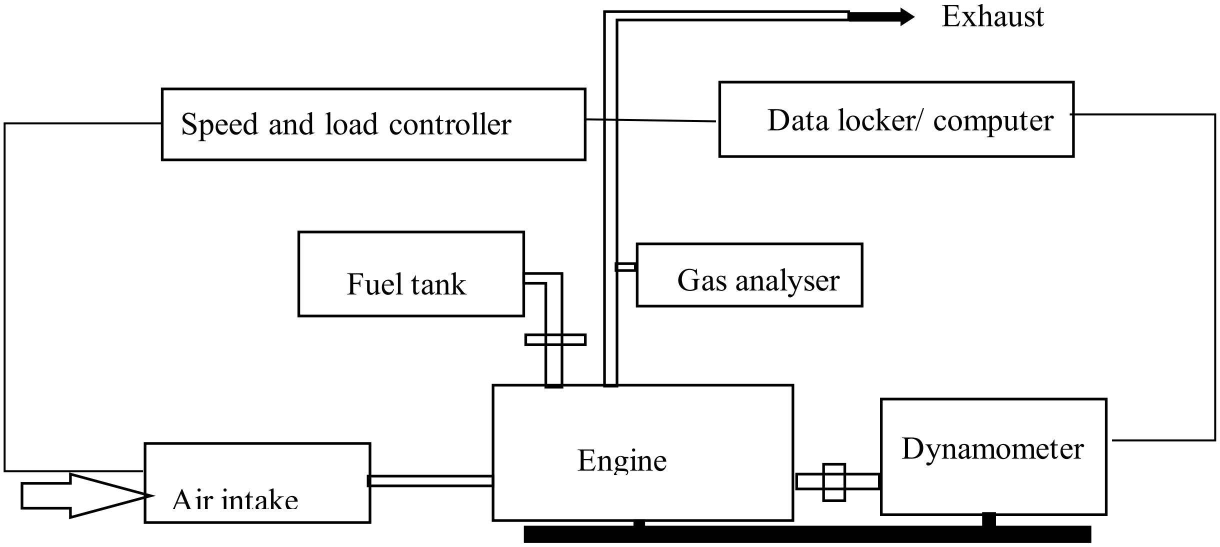

Figure 1: **Experimental Setup**

The experiments were conducted using factorial experimental designs, as shown in Table 1 below.

Table 1: Engine Test Modes

Input Parameters	**Input Range**				
Sources of Biodiesel,	WVO	Coconut	Sunflower	Canola	Oleander
Biodiesel blends (Bi),%	10	15	20	25	30
Load (W), kg ((Bp), kW)	0 (0)	3(0.86)	6(1.72)	9(2.58)	12(3.44)

Engine performance and emissions were evaluated using Brake thermal efficiency (Bte), specific fuel consumption (Sfc), carbon monoxide (CO) and nitrogen oxides (NOx).

Optimisation of Engine Performance using NSGA II

The optimisation process for compression ignition (CI) engines used Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and the prediction models for engine performance (Bte) and emissions (CO and NOx) developed by Kibiwot et al. (2024). The models were;

$$Bte = 1.2B^{-0.42}\left(\frac{Bp}{\rho\vartheta^2 {C_p}^{1/2}}\right)^{0.68} \text{ .... (1)}$$

$$CO = 0.03B^{-0.12}\left(\frac{Bp}{\rho\vartheta^2 {C_p}^{1/2}}\right)^{-0.35} \text{ .... (2)}$$

$$NOx = 24000B^{0.16}\left(\frac{Bp}{\rho\vartheta^2 {C_p}^{1/2}}\right)^{1.3} \text{ .... (3)}$$

where:

Bte = bake thermal efficiency; *B* = blend percentage of biodiesel
Bp = equivalent brake power; ϑ = kinematic viscosity of the biodiesel
CO = carbon monoxide ρ = density of the biodiesel
NOx= nitrogen oxide

In this research, a random initial population of size was generated within the variable ranges of the models above. The design space (constraints) for the input parameters that affected Bte and NOx emissions were defined as;

a) Blend level range; $0.1 \leq B \leq 0.3$
b) Carbon monoxide limit; CO ≤ 1500 ppm

The objective functions were established as the maximisation of Bte and minimisation NOx using equations 1, 2 and 3 in the constraints limits of a and b. The Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) determined Pareto fronts using the ranking method. NSGA-II was used to identify optimal points based on the application and priorities from the Pareto front, representing a balance between Bte and NOx. The NSGA II was run on the MATLAB gamultiobj non-linear constraint functions code to give results for the optimal blends.

4.0 RESULTS AND DISCUSSIONS

Fuel Properties

The selected biodiesel properties, density, kinematic viscosity and lower heating value were determined using ASTM D1298, ASTM D445-18 and ASTM D2015-18 procedures, respectively. The measurements for the fuel properties were replicated three times and recorded. Their data was analysed using ANOVA and Tukey pairwise test, as presented in Table 2.

Table 2: Determined Properties of the Selected Biodiesels

Selected fuel Properties	Diesel	WVO	Coconut	Canola	Sunflower	Oleander	LSD
Density (p), kg/m3@23°c	820.0^f	876.6^d	872.3^e	891.6^b	882.9^c	925.1^a	0.170
Kinematic viscosity, mm^2/s@40°c	3.2^f	4.2^e	4.4^d	4.7^c	5.2^b	5.5^a	0.033
heat value (Cv) kJ/kg	43906^a	39421^b	38736^c	37572^e	37818^d	36206^f	0.043

Key: The superscript letters (a, b ...f) represent specific property groups significantly different from each other, as ranked according to the status; that is, 'a' has the highest value and 'f' lowest

Oleander had the highest density among the biodiesels, while diesel had the lowest compared to all biodiesels. The LSD - 0.170 and P < 0.0001 (σ = 0.05) showed that there were considerable differences in the densities of the biodiesel blends. The kinematic viscosity of oleander was highest amongst the biodiesels, while diesel recorded the lowest compared to all biodiesels, with their LSD - 0.033 and P < 0.0001 (σ = 0.05) indicating significant. The low heating value of diesel was higher than that of biodiesel fuel, with WVO having the lowest lower heat value and coconut having the lowest heat value. The small LSD of 0.043 and P < 0.001 shows that there was a statistically important difference in lower heat value.

Engine Performance and Emissions

The single-cylinder VCR engine performance parameters tests are presented in the sub-sections below;

a) Brake Thermal Efficiency

The data presented in Table 3 were obtained from an experimental study analysing the brake thermal efficiency (Bte) of a CI engine fueled with different biodiesel sources.

Table 3: **Brake Thermal Efficiency of the Biodiesels**

bp (kW)	**WVO**	**Coconut**	**Canola**	**Sunflower**	**Oleander**	**LSD**
0.83	3.64^{ab}	3.78^{a}	3.48^{b}	2.63^{c}	1.51^{d}	0.0501
1.17	5.64^{a}	5.69^{a}	4.64^{b}	4.24^{b}	2.68^{c}	0.0726
1.74	9.5^{a}	8.38^{b}	7.15^{c}	5.91^{d}	4.46^{e}	0.1785
2.13	10.49^{a}	9.61^{b}	7.97^{c}	7.62^{d}	5.83^{e}	0.0115
2.82	12.44^{a}	11.52^{b}	9.69^{c}	9 ^{d}	6.89^{e}	0.01154
3.43	13.5^{a}	12.06^{b}	10.38^{c}	9.4^{d}	7.64^{e}	0.01150

The values with the same letter in the same row are not significantly different at P-value < 0.0001

Table 3 shows that the Bte was higher when the engine was operated at higher brake power (bp). WVO biodiesel produced higher Bte compared to the other biodiesels, while oleander had the lowest Bte value. The P- P-value <0.0001 and LSD values ranging from 0.0057 - 0.0997 are very small, implying that the means of the Bte of the biodiesel were statistically different for the different bp levels.

b) Carbon Monoxide Emissions

The carbon monoxide (CO) emissions for various biodiesel and diesel at different equivalent brake power levels are shown in Table 4 below.

Table 4: **Carbon Monoxide Emissions for Biodiesels**

bp, (kW)	**Carbon monoxide emissions, ppm**						
	WVO	**Coconut**	**Canola**	**Sunflower**	**Oleander**	**Diesel**	**LSD**
0.83	1247^{f}	1359^{e}	1411^{d}	1553^{b}	1516^{c}	2128^{a}	0.5774
1.17	1208^{f}	1310^{e}	1379^{d}	1461^{b}	1434^{c}	2123^{a}	0.578
1.72	1058^{f}	1209^{e}	1270^{d}	1361^{b}	1320^{c}	2009^{a}	0.5771
2.13	895^{f}	1008^{e}	1029^{d}	1181^{b}	1013^{c}	1796^{a}	0.5775
2.82	673^{f}	846^{e}	916^{d}	959^{b}	969^{c}	1554^{a}	0.5779
3.43	672^{f}	784^{e}	836^{d}	908^{b}	909^{c}	1554^{a}	0.5784

The values with the same letter in the same row are not significantly different at P-value < 0.0001

From Table 4, the CO emissions from the engine were higher at high bp while lower when the engine was at low bp. Diesel produces higher emissions of CO than any of the biodiesel fuels used. Oleander biodiesel produced higher CO emissions than all other biodiesels. The low P-value (<0.0001) indicates that there is a statistically substantial difference in CO emissions between the different fuels at each brake power level. Typically, a P < 0.0001 is considered significant at a 95 per cent confidence level. LSD ranged from 0.5763 to 0.5784, implying that there was a substantial difference in CO emissions.

c) Nitrogen Oxides Emissions

Nitrogen oxides (NOx) for the biodiesel blend and diesel at bp are shown in Table 5 below.

Table 5: Nitrogen Oxides for Biodiesels Compared to Diesel

	Biodiesels						
bp, kW	**WVO**	**Coconut**	**Canola**	**Sunflower**	**Oleander**	**Diesel**	**LSD**
0.83	79^a	77^a	65^c	72^b	57^d	22^e	0.5793
1.17	102^a	94^b	77^d	85^c	65^e	28^f	0.6871
1.74	129^a	122^b	102^d	106^c	84^e	46^f	0.5778
2.13	153^a	144^b	122^d	135^c	113^e	61^f	0.5722
2.82	210^a	198^b	169^d	174^c	151^e	89^f	0.5761
3.43	249^a	241^b	210^d	220^c	194^e	109^f	0.5984

The values with the same letter in the same row are not significantly different at P-value < 0.0001

WVO biodiesel produced the highest NOx emissions at all bp levels, as shown in Table 5, followed by Coconut, sunflower, canola, Oleander, and diesel produced the lowest emissions. The results showed that as the bp increased, the NOx emissions increased, and highly significant differences in NOx emissions between the biodiesel fuels, with p-values less than 0.0001. The LSD ranged from 0.5761-0.5784, implying statistical differences among the NOx emissions from different biodiesels.

Optimisation of the Biodiesel Blends Blending

The Non-sorting genetic algorithm (NSGA-II) was used to determine the optimal blending level for each biodiesel (WVO, canola, sunflower, oleander, and coconut). The conflicting performance and emissions metrics {maximising Bte while minimising CO and NOx} for biodiesels' blends are presented below;

a) Brake Thermal Efficiency Optimisation

The results presented in Table 6 were the Bte values for the optimal biodiesel' blends and their comparisons to the Bte of the engine when fueled by diesel.

Table 6: Brake Thermal Efficiency Optimum Results

Biodiesel	**WVO**	**Canola**	**coconut**	**Sunflower**	**Oleander**
Optimal blend (%)	22.5	19	19.6	18.7	20.1
Bte at an optimal blend	21.9	23.6	23.3	23.7	23.0
Bte per cent Change	9.8	2.9	4.2	2.3	5.2

From experiments Bte Diesel = 24.3 % obtained; Bte percent change = (Bte optimal - Bte Diesel)/Bte diesel

Table 6 shows that the biodiesels lowered Bte by 2 to 10 per cent compared to diesel; the highest decrease was observed for WVO at 9.8 per cent. The lower Bte values were marginally small; thus, the optimal blend for biodiesels can serve as a substitute for diesel without significant impacts on the performance of compression ignition engines (Ghazali et al., 2015).

b) Carbon Monoxide Optimisation

The results presented in Table 7 were the CO values for the optimal biodiesel' blends and their comparisons to the CO of the engine when fueled by diesel.

Table 7: Carbon Monoxide Optimization Results

Biodiesel	**WVO**	**Canola**	**Coconut**	**Sunflower**	**Oleander**
Optimal blend (%)	22.5	19	19.6	18.7	20.1
CO at an optimal blend	1500	1531	1525	1534	1520
CO per cent change	21.2	19.6	19.9	19.5	20.2

From experiments CO Diesel = 1904ppm; CO percent Change = (CO optimal - CO Diesel)/CO diesel

The engine ran on 22.5 per cent WVO, 19 per cent canola, 19.6 per cent coconut, 18.7 per cent sunflower and 20.1 per cent Oleander biodiesel blends' demonstrated a decrease of 21, 20, 20, 19 and 20 per cent reduction in CO emission, respectively, as compared to diesel as shown in Table 7. Using optimal biodiesel,' blends demonstrated substantial CO emission reductions of approximately 20 per cent for the CI engine.

c) Nitrogen Oxides Emissions

The results presented in Table 8 were the NOx values for the optimal biodiesel' blends and their comparisons to the NOx of the engine when fueled by diesel.

Table 8: Nitrogen Oxide Optimisation Results

Biodiesel	**WVO**	**Canola**	**Oleander**	**Sunflower**	**Coconut**
Optimal blend (%)	22.5	19	19.6	18.7	20.1
NOx at an optimal blend	139.0	135.3	135.9	134.9	136.5
NOx per cent change	6.9	4.1	4.6	3.8	5.0

From experiments NOx for Diesel = 130ppm; NOx percent Change = (NOx optimal - NOx Diesel)/ NOx diesel

The NOx emissions from the engine fueled by biodiesel blends averaged 136 ppm compared to diesel at 130 ppm, a marginal increase of approximately 5 per cent, but within regulated limits.

5.0 CONCLUSION AND RECOMMENDATION

Conclusion: The tests on the CI engine demonstrated that the blends B22.5, B19, B19.6, and B18.7 for WVO, canola, oleander, coconut, and sunflower biodiesels, respectively, offer the best trade -off between reducing harmful emissions and maintaining reliable engine performance.

Recommendation: Whereas the model offers a starting point for simulating biodiesel blend combustion in compression ignition (CI) engines, there is a need to expand the model inputs to cover a wider range of the biodiesel fuel properties, the different engine types and real -world operating conditions. Essentially, this shall leverage the model's applicability and improve its computational efficiency to ensure its reliability.

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