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Experimental Investigation of Diesel Engine Emissions Using Blends of Waste Vegetable Oils

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Abstract
At the present time, the energy crisis, climate and air pollution represent major global problems in addition to the high prices of fossil fuel and vegetable oils. These problems were increased with the current global conflicts which have led to an increase in global warming and rising global temperatures causing significant climate change in many regions of the world. A carbon dioxide emission is one of the main pollutants that cause an increase in global warming. Waste vegetable oils can be used directly as an alternative fuel in diesel engines because they are environmentally friendly. In this paper, the effect of used waste vegetable oils on the emissions of a diesel engine with different blends compared to pure diesel fuel was studied. One of the important results of this research is that with the increase in the proportion of used waste vegetable oil blend in the fuel; it leads to a decrease in carbon dioxide emissions. Carbon dioxide emissions increase by 5 % and 10.13 % for B20-WPKO and B20-WSFO fuels respectively compared to pure diesel fuel at 60 % of load and carbon dioxide emissions decrease by 12.66 % and 7.6 % for B40-WPKO and B40-WSFO fuels respectively compared to pure diesel fuel at 60% of load. The use of these oils has led to a further decrease in carbon dioxide emissions, and thus a decrease in global warming, furthermore re-processing and reusing these oils is harmful to human health.

1. **Introduction**

Vegetable oils are considered an alternative fuel and they are used directly in diesel engines, since these oils are environmentally friendly, because the carbon dioxide gas does not go out to the atmosphere because of absorption from the crops of these oils. The production process of vegetable oil involves the removal of oil from plant components, typically seeds. Many investigators studied the effect of vegetable oils or biodiesel produced from vegetable oils on the emissions of diesel engine, as a fuel such as hazelnut oil [1], sunflower oil, cotton oil, soybeans oil, corn oil, olive oil [2 , 3 , 4 and 5], palm oil [5, 6 and 7], coconut oil [8 and 9], jatropha oil [10 and 11], cooking oil [12 and 13], safflower oil, biodiesel [14],

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waste frying oil methyl ester [15 and 16], rapeseed methyl ester [17 and 18], rubber seed oil methyl ester [19], palm oil ethyl ester [20], waste cooking oil [21], waste cooking oil methyl ester [22], lemon balm oil [23], lemon peel oil biodiesel [24], coconut oil methyl esters [25] and dairy scum oil biodiesel [26] . Differences in results were observed because of some reasons such as using of different biofuels and diesel fuel in each investigation. From previous studies: the focus has been on various exhaust gas emissions, including carbon dioxide emissions, where CO_2 represents the maximum percentage of greenhouse gases emitted by human activities. In 2020, carbon dioxide accounted for about 79% of all greenhouse gas emissions in the United States from human activities [27]; as it is the main gas which is responsible for the increase in global warming. Therefore, we will use waste vegetable oils in this research because they are environmentally friendly (CO_2 does not go out to the atmosphere).
The aim of this study is to carry out experimental investigation into exhaust emission (CO, CO_2, CH, NO_X and O_2) of diesel engine fuelled with waste palm kernel oil (WPKO) and waste sunflower oil (WSFO) blends compared to those of diesel fuel. These oils reduce the proportion of harmful emissions; including carbon dioxide emissions, where this gas do not go out to the atmosphere, which leads to a decrease in global warming in addition to re-processing and reusing these oils is harmful to human health.

2. Materials and Methods

This section presents details of the experimental test rig. The components of the experimental set-up are presented and the measuring devices used are shown with an indication of their accuracy.

2.1. Experimental Set-up and Test Procedure

An air cooled, single cylinder, four stroke, DEUTZ F1L511 model and direct injection diesel engine was employed as a test engine in this study. The engine has 100 mm bore, 105 mm stroke, compression ratio of 17 and a rated brake power of 5.7 kW at 1500 rpm. Schematic diagram and the pictorial view of the experimental set-up are shown in Figure 1. An electrical dynamometer with maximum electrical power output of 15 HP has been directly coupled to the engine output shaft. The engine operates at a certain load (percentage of the maximum torque) when the excitation field voltage (applied on the electrical dynamometer) is adjusted to produce a specified engine output power. The values of the excitation field voltage corresponding to the prescribed engine load have been variation at constant engine speed (1500 rpm) and injection pressure (170 bars) during test. The optical tachometer was used to measure the engine speed with ±0.01% accuracy.
Compositions of exhaust gases (CO, CO_2, HC, NO_X and O_2) were obtained by extracting a continuous sample of exhaust gases through the exhaust pipe. The exhaust gases were then fed into the gas analyzers and measured by the sensors with accuracies shown in table 1 for these measured compositions.

Table 1: Accuracies of the exhaust gases compositions

CO	**CO_2**	**HC**	**NO_X**	**O_2**
±0.01%	±0.2%	±0.2%	±10 ppm	±0.2%

The plan which designed for the experimental investigation on emissions of diesel engine is to use six blends of WVO, three kinds of WPKO blends with DF (by volume) and three kinds of WSFO blends with DF (by volume) compared with DF; see table 2. The volume of the fuel used can be calculated from equation 1; BR=0 for pure diesel fuel and BR=1 for pure WVO.

$$\mathbf{V_{fuel\ used} = (1\text{-}BR) * V_{DF} + BR * V_{WVO}} \qquad \textbf{(1)}$$

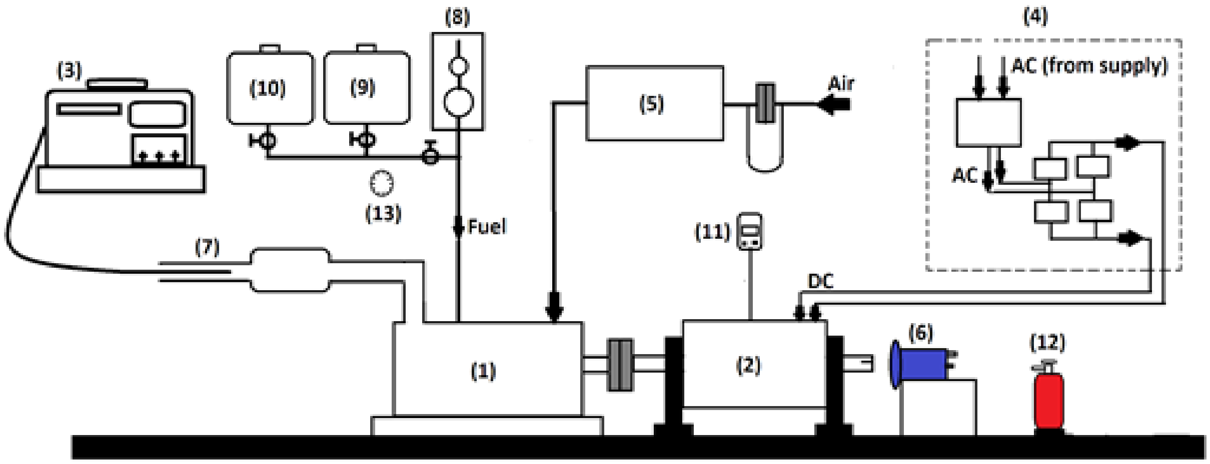


Figure 1(a): Schematic diagram of the experimental setup

Figure 1(b): Pictorial view of the experimental set-up

(1) Diesel Engine
(2) Electrical Dynamometer
(3) Exhaust Gas Analyzer
(4) Voltage Regulator
(5) Air Box
(6) the Optical Tachometer
(7) Exhaust Gases Pipes
(8) Fuel Consumption Rate Device
(9) Biofuel Tank
(10) Diesel Fuel Tank
(11) The Digital Weight
(12) Fire Extinguisher
(13) Stopwatch

Figure 1: Schematic diagram and pictorial view of the experimental set-up

Table 2: Six kinds of WVO blends

BR	No. of Blend	DF	WPKO	Blend (DF+WPKO)	No. of Blend	DF	WSFO	Blend (DF+WSFO)
0.2	1	80%	20%	B20-WPKO	4	80%	20%	B20-WSFO
0.3	2	70%	30%	B30-WPKO	5	70%	30%	B30-WSFO
0.4	3	60%	40%	B40-WPKO	6	60%	40%	B40-WSFO

Main properties of the fuel tested are shown in table 3. As shown in this table: pure diesel has the highest gross calorific value, highest Cetane number, lowest viscosity, and lowest density. When diesel mixed with WVO to make blends, it was found that the more percentage of WVO in the blends, it leads to an increase in the viscosity, density, gross calorific value, and a decrease in the cetane number of the blend compared with diesel fuel.

Table 3: Fuel Properties [2, 28, 29, 30 and 31]

Fuel	Calorific value (kJ/kg)	Viscosity (mm^2/s) at 35 °C	Density (ρ) (kg/m3)	Cetane No. (CN)	Chemical Formula
DF	42700	5	780	48	$C_{10.8}H_{18.7}$
Pure WPKO	37200	69.6	835	36.5	$C_{16}H_{32}O_2$
Pure WSFO	37000	67.7	845	37	$C_{57}H_{103}O_6$

3. Results and Discussion

In this section, results obtained from the experimental investigation are presented and discussed. The effect of engine loads on the engine emissions for all used waste vegetable oils blends with diesel fuel are investigated. Comparison of all obtained results with pure diesel fuel are presented and discussed.

3.1. Effect of Engine Load on Carbon Monoxide Emissions

Figure 2 shows the variation of CO emissions with engine load at constant engine speed for WVO blends compared with DF. The emissions of CO increase with increasing the engine load compared with DF for all blends. Also, CO emissions increased with rising in the concentration of WVO in blend compared with DF; this is due to higher carbon content in WVO blends compared with DF. Also, the rising trend of CO emission with engine load is due to increasing the amount of fuel entering the engine with increasing engine load [1, 2, 6, 11 and 16]. Equations for the fitting curves of CO emissions as a function of engine load are shows below for different fuel types.

For DF : $Y = 0.22 + 0.002416666667 * X + 0.0001 * X^2 - 1.041666667E\text{-}006 * X^3$

For B20-WPKO : $Y = 0.23 + 0.002583333333 * X + 8.75E\text{-}005 * X^2 - 8.333333333E\text{-}007 * X^3$

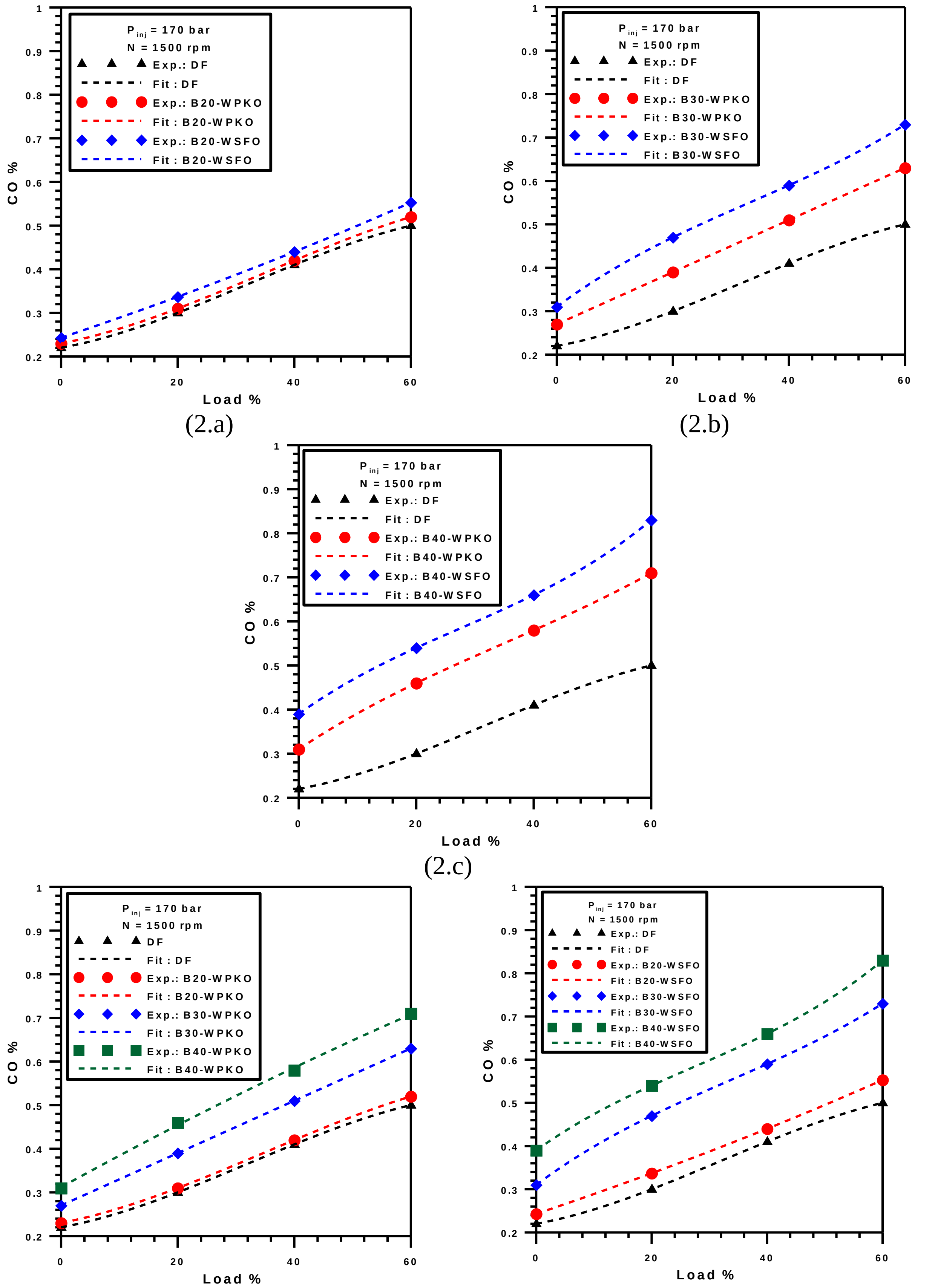
For B20-WSFO : $Y = 0.243 + 0.004491666667 * X + 1E\text{-}005 * X^2 + 2.083333333E\text{-}008 * X^3$

For B30-WPKO : $Y = 0.27 + 0.006 * X + 2.602085214E\text{-}020 * X^2 - 2.891205793E\text{-}022 * X^3$

For B30-WSFO : $Y = 0.31 + 0.01 * X - 0.000125 * X^2 + 1.25E\text{-}006 * X^3$

For B40-WPKO : $Y = 0.31 + 0.008916666667 * X - 8.75E\text{-}005 * X^2 + 8.333333333E\text{-}007 * X^3$

For B40-WSFO : $Y = 0.39 + 0.009583333333 * X - 0.0001375 * X^2 + 1.666666667E\text{-}006 * X^3$



(2.a) (2.b) (2.c) (2.d) (2.e)

Figure 2: Effect of engine load on carbon monoxide emissions for different blends of WPKO and WSFO compared with DF.

3.2. Effect of Engine Load on Carbon Dioxide Emissions

Figure 3 presents experimental results of CO_2 for different WVO blends versus engine loads at constant engine speed. The emissions of CO_2 increase with increasing the load compared with DF for B20-WPKO and B20-WSFO. Then, CO_2 emissions decrease with the increase in the load and increase in WVO blends compared with DF for B30 and B40 for fuel used. So, CO_2 emissions for WVO blends decrease with increase of WVO volume percentage due to the increase in oxygen content in WVO blends compared with DF [1, 2, 5, 16, 17 and 20]. The fitting curves equations for CO_2 emissions as a function of engine load are presents below for different fuel types.

For DF : $Y = 3.87 - 0.03783333333 * X + 0.0032 * X^2 - 2.416666667E\text{-}005 * X^3$

For B20-WPKO : $Y = 3.97 - 0.01558333333 * X + 0.002425 * X^2 - 1.604166667E\text{-}005 * X^3$

For B20-WSFO : $Y = 4.1 - 0.01333333333 * X + 0.00325 * X^2 - 2.916666667E\text{-}005 * X^3$

For B30-WPKO : $Y = 3.73 - 0.03108333333 * X + 0.00295 * X^2 - 2.354166667E\text{-}005 * X^3$

For B30-WSFO : $Y = 3.91 - 0.03591666667 * X + 0.003275 * X^2 - 2.520833333E\text{-}005 * X^3$

For B40-WPKO : $Y = 3.13 + 0.0005833333333 * X + 0.001575 * X^2 - 8.958333333E\text{-}006 * X^3$

For B40-WSFO : $Y = 3.41 - 0.003416666667 * X + 0.002275 * X^2 - 1.895833333E\text{-}005 * X^3$

3.3. Effect of Engine Load on HC Emissions

The variation of HC measured with various engine loads for WVO blends compared with DF at constant engine speed is shown in Figure 4. HC emission is lower at no load and increases with increase of engine load. WVO blends produced higher HC emissions at all engine loads compared to diesel fuel. Increase of WPKO or WSFO percentage in WVO blends leads to increase the HC emissions due to the higher carbon atoms; and the C/H ratio in WVO compared with DF [1, 16 and 17]. Equations for the fitting curves of HC emissions as a function of engine load are illustrates below for different fuel types.

For DF : $Y = 7 + 0.09166666667 * X + 1.665334537E\text{-}018 * X^2 + 2.0833E\text{-}005 * X^3$

For B20-WPKO : $Y = 9 + 0.09166666667 * X + 1.665334537E\text{-}018 * X^2 + 2.0833E\text{-}005 * X^3$

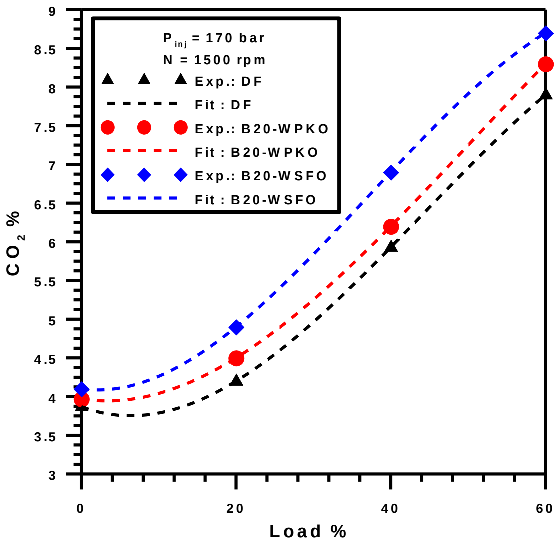
For B20-WSFO : $Y = 10 + 0.1083333333 * X - 0.00125 * X^2 + 4.166666667E\text{-}005 * X^3$

For B30-WPKO : $Y = 12 + 0.1833333333 * X - 0.0025 * X^2 + 4.166666667E\text{-}005 * X^3$

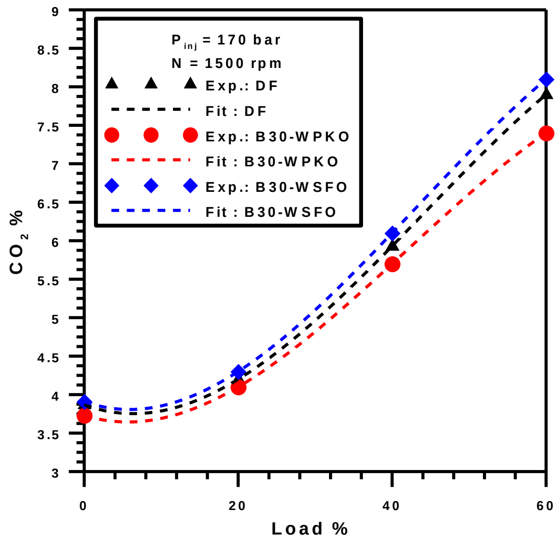
For B30-WSFO : $Y = 14 + 0.125 * X + 0.00125 * X^2 + 4.625929269E\text{-}021 * X^3$

For B40-WPKO : $Y = 15 + 0.01666666667 * X + 0.005 * X^2 - 4.166666667E\text{-}005 * X^3$

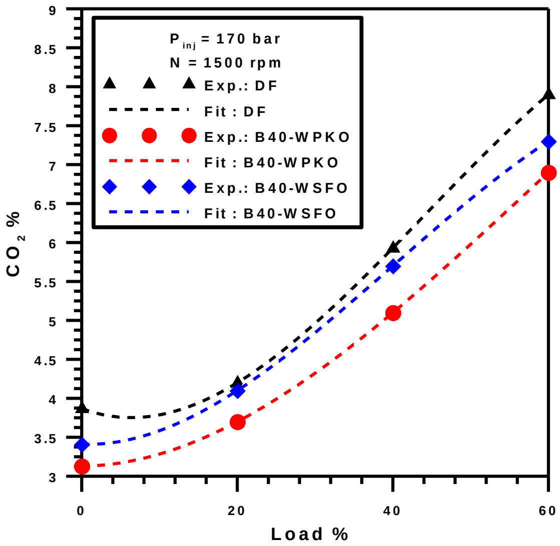
For B40-WSFO : $Y = 17 - 0.025 * X + 0.0075 * X^2 - 6.25E\text{-}005 * X^3$



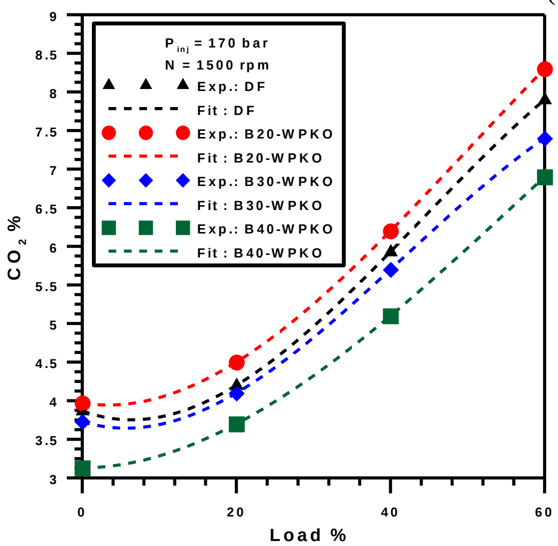
(3.a)



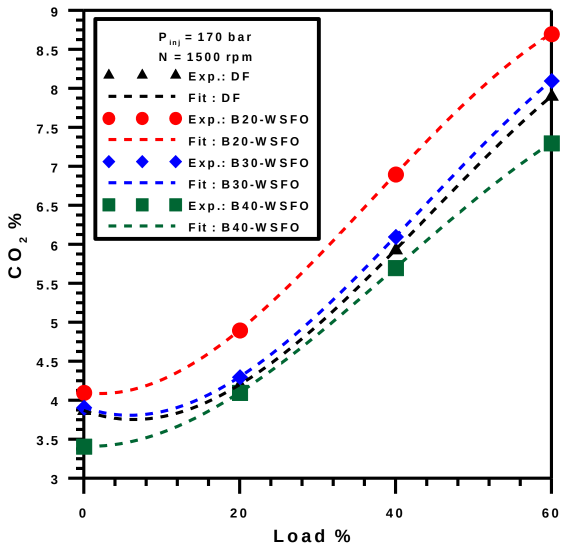
(3.b)



(3.c)



(3.d)



(3.e)

Figure 3: Effect of engine load on carbon dioxide emissions for different blends of WPKO and WSFO compared with DF

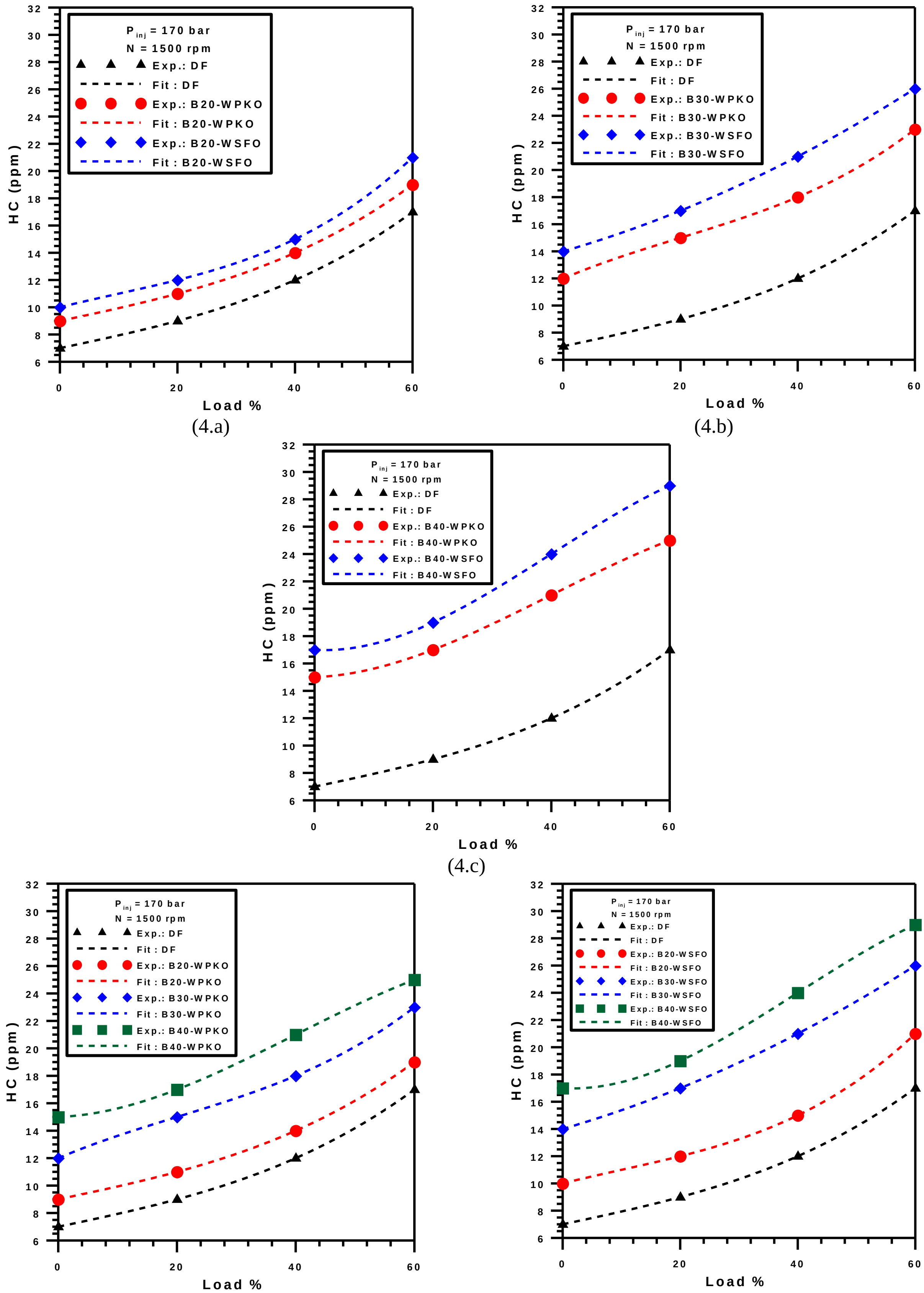


Figure 4: Effect of engine load on HC emissions for different blends of WPKO and WSFO compared with DF

3.4. Effect of Engine Load on Nitrogen Oxides Emissions

Figure 5 shows the variation of NO_X emission with engine load for WVO blends at constant engine speed biodiesel blends. NO_X emission is more for WVO blends than that for diesel fuel. The rising trend of NO_X emission with engine load is due to the higher fuel entry as the load increased. NO_X emissions for WVO blends were higher than diesel fuel and it increases with the increase in blend proportion. NO_X emission increase is due to increase of fuel burned and the temperature gas in the cylinder which is responsible for thermal NO_X formation [5, 6, 11, 18, 22, 23 and 25]. The fitting curves equations for NO_X emissions as a function of engine load are shows below for different fuel types.

For DF : $Y = 367 + 1 * X + 0.08 * X^2 - 0.00075 * X^3$

For B20-WPKO : $Y = 378 + 0.975 * X + 0.08625 * X^2 - 0.000875 * X^3$

For B20-WSFO : $Y = 393 - 0.15 * X + 0.1175 * X^2 - 0.001 * X^3$

For B30-WPKO : $Y = 391 + 3.25 * X - 0.01125 * X^2 + 0.0003125 * X^3$

For B30-WSFO : $Y = 433 + 1.866666667 * X + 0.07 * X^2 - 0.0006666666667 * X^3$

For B40-WPKO : $Y = 411 - 0.4666666667 * X + 0.205 * X^2 - 0.002083333333 * X^3$

For B40-WSFO : $Y = 457 + 0.3333333333 * X + 0.155 * X^2 - 0.001583333333 * X^3$

3.5. Effect of Engine Load on Oxygen Emissions

Figure 6 presents the effect of engine loads on O_2 measured at constant engine speed. According to the outcomes, O_2 emissions decrease with the addition of WVO content in the fuel blends and Oxygen emissions decrease with the increase in load for all fuels used. Moreover, diesel fuel is the highest level of O_2 emissions. Decreases in oxygen emissions for WVO blends were due to the higher carbon atoms; the C/H ratio in the fuel and reduction air fuel ratio for WVO blends compared with DF [10 and 20]. Equations for the fitting curves of O_2 emissions as a function of engine load are presents below for different types of fuels.

For DF : $Y = 17.1 - 0.1075 * X + 0.00225 * X^2 - 1.875E-005 * X^3$

For B20-WPKO : $Y = 14.7 - 0.001666666667 * X - 0.005 * X^2 + 5.416666667E-005 * X^3$

For B20-WSFO : $Y = 13.7 - 0.03166666667 * X - 0.00375 * X^2 + 4.166666667E-005 * X^3$

For B30-WPKO : $Y = 13.3 - 0.08666666667 * X - 0.001125 * X^2 + 1.041666667E-005 * X^3$

For B30-WSFO : $Y = 12.8 - 0.08083333333 * X - 0.0015 * X^2 + 1.458333333E-005 * X^3$

For B40-WPKO : $Y = 12.1 - 0.06833333333 * X - 0.00125 * X^2 + 8.333333333E-006 * X^3$

For B40-WSFO : $Y = 11.1 - 0.075 * X - 0.000875 * X^2 + 6.25E-006 * X^3$

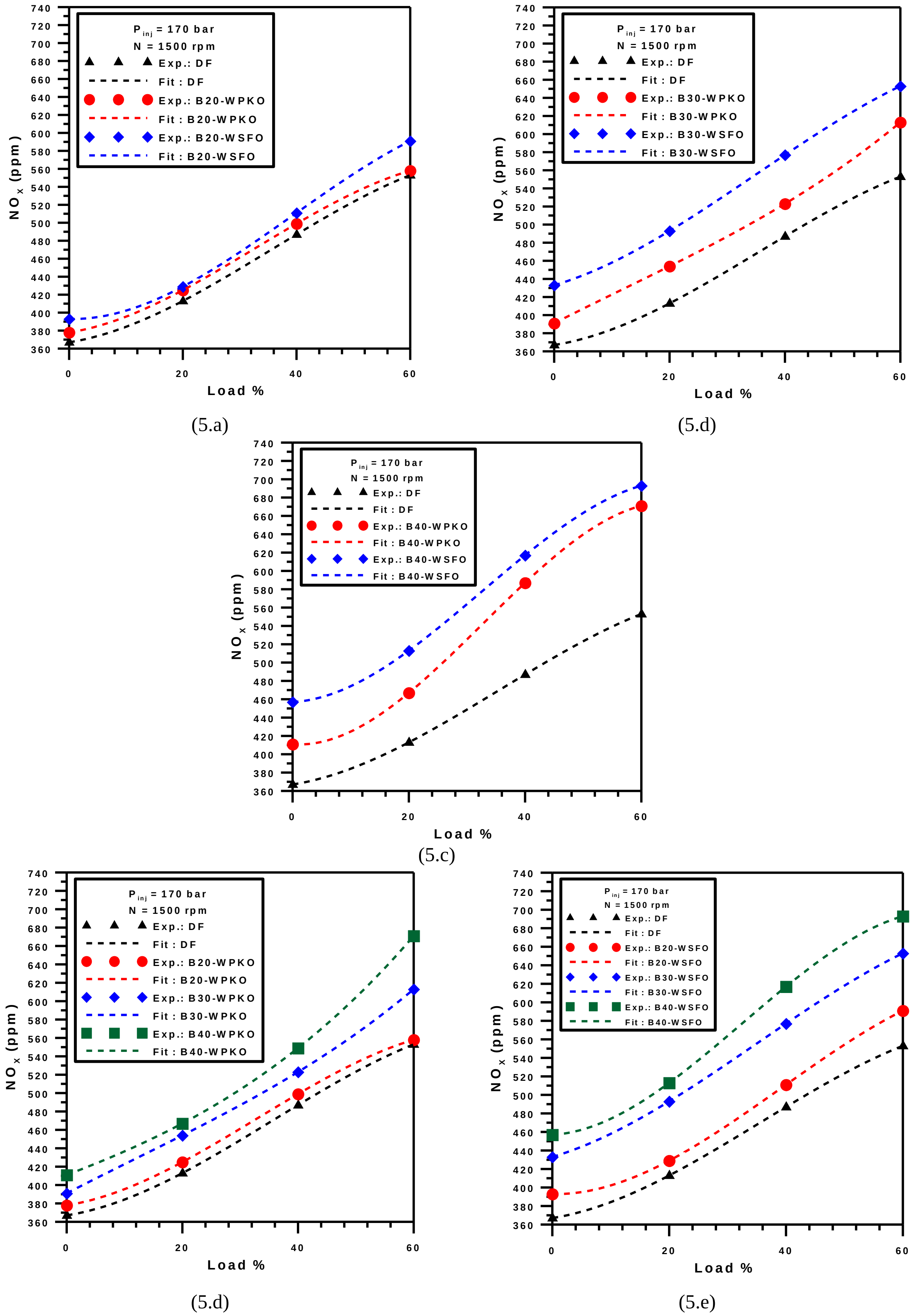
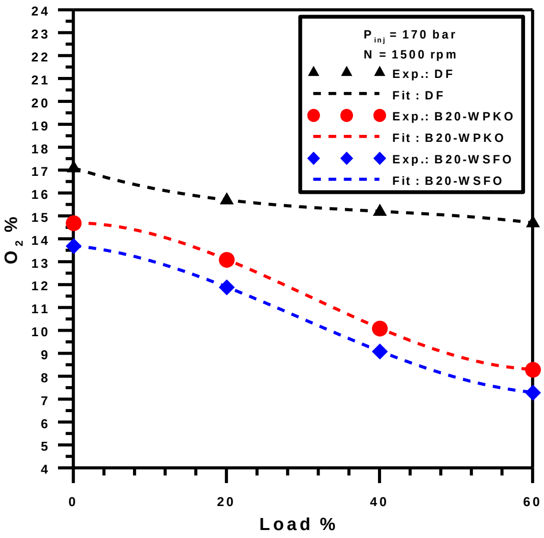
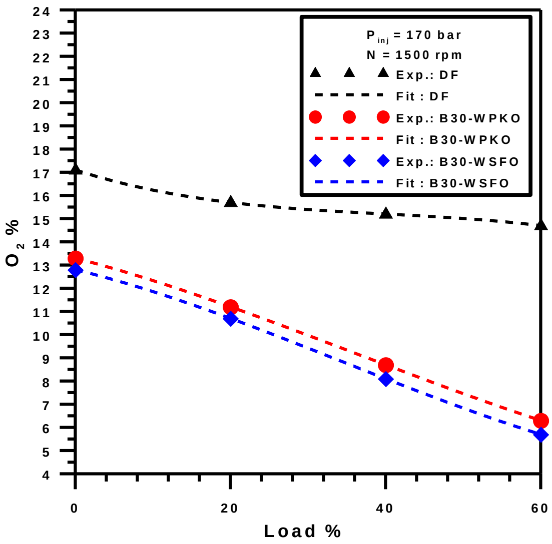


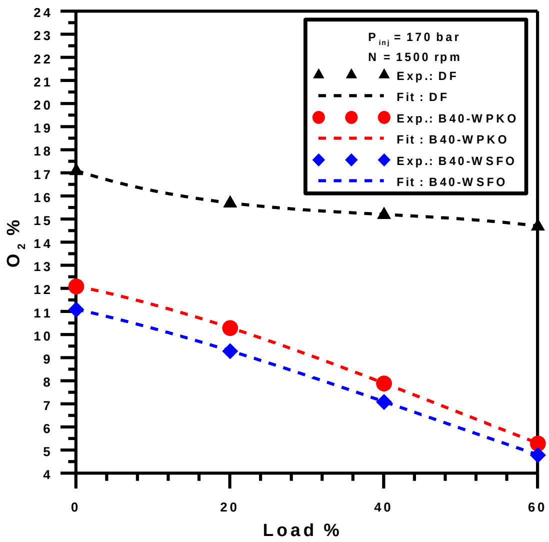
Figure 5: Effect of engine load on Nitrogen Oxides emissions for different blends of WPKO and WSFO compared with DF



(6.a)



(6.b)



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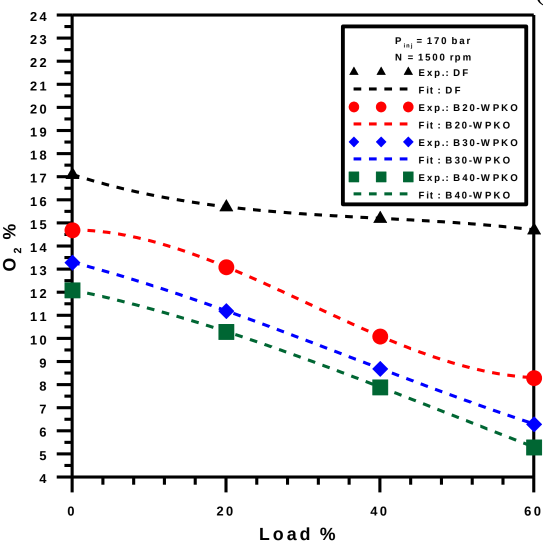
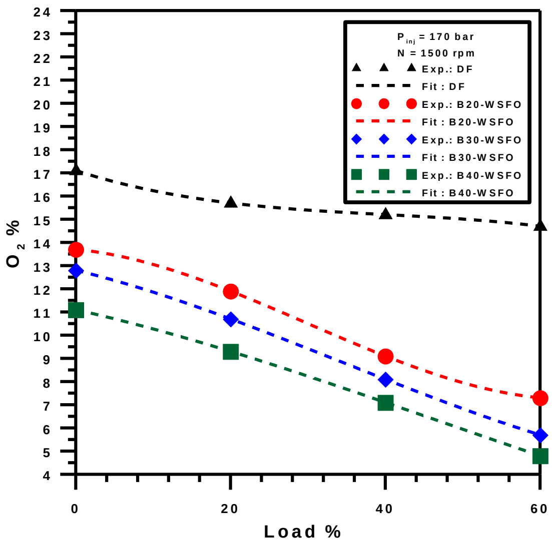


(6.d)



(6.e)

Figure 6: Effect of engine load on Oxygen emissions for different blends of WPKO and WSFO compared with DF

4. Conclusions

An experimental investigation of the exhaust gas emissions of a diesel engine using DF and blends of WVO with DF was conducted. The following conclusions were obtained:

- The emissions of CO increase with the increase in engine load and the CO increase with increase in WVO blends compared with DF at all engine loads. In general, CO emissions increase by 6 %, 26 % and 42 % for B20-WPKO, B30-WPKO, and B40-WPKO fuels respectively compared to diesel fuel at 60 % of engine load, and also CO emissions increase by 10.6 %, 46 % and 66 % for B20-WSFO, B30-WSFO, and B40-WSFO fuels respectively, compared to diesel fuel at 60% of load.
- The emissions of CO_2 increase with the increase in engine load. CO_2 emissions increase by 5 % and 10.13 % for B20-WPKO and B20-WSFO fuels respectively compared to diesel fuel at 60 % of load and also CO_2 emissions decrease by 12.66 %, and 7.6 % for B40-WPKO and B40-WSFO fuels respectively compared to diesel fuel at 60% of load.
- The emissions of HC increase with the increase in engine load and the HC increase with the increase in WVO blends compared with DF at all engine load. In general, HC emissions increase by 11.7 %, 35.3 % and 47.1 % for B20-WPKO, B30-WPKO, and B40-WPKO fuels respectively compared to diesel fuel at 60 % of load and also CO emissions increase by 23.5 %, 52.9 % and 70.6 % for B20-WSFO, B30-WSFO, and B40-WSFO fuels respectively compared to diesel fuel at 60% of load.
- The emissions of NO_X increase with the increase in engine load and the NO_X increase with increase in WVO blends compared with DF at all engine load. In general, NO_X emissions increase by 0.9 %, 10.85 % and 28 % for B20-WPKO, B30-WPKO, and B40-WPKO fuels respectively compared to diesel fuel at 60 % of load an also CO emissions increase by 9 %, 25.32 % and 32.5 % for B20-WSFO, B30-WSFO, and B40-WSFO fuels respectively compared to diesel fuel at 60% of load.
- On average, O_2 emissions decrease by 43.5 %, 57.1 % and 76 % for B20-WPKO, B30-WPKO, and B40-WPKO fuels respectively compared to diesel fuel at 60 % of engine load and also O_2 emissions decrease by 50.3 %, 61.2 % and 67.3 % for B20-WSFO, B30-WSFO and B40-WSFO fuels respectively compared to diesel fuel at 60% of engine load.

Based on these results and CO_2 emissions, it can be concluded that the fuel derived from waste vegetable oil can serve as an alternative fuel for diesel engines because it reduces global warming due to lower CO_2 emissions. The percentages of increase or decrease in the exhaust gases measurements for all waste vegetable oil blends compared to diesel fuel are shown in the figures in the appendix.

Abbreviations

CO	Carbon Monoxide	**CO_2**	Carbon Dioxide
DF	Diesel Fuel	**HC**	Unburned Hydrocarbons
NO_X	Nitrogen Oxides	**O_2**	Oxygen
ppm	Parts per million	**rpm**	Revelation per minute
WPKO	Waste Palm Kernel Oil	**WSFO**	Waste Sunflower Oil
WVO	Waste Vegetable Oils	**BR**	Blend ratio by volume

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APPENDIX

$$\%age.increase\ or\ decrease\ in\ Item = \left[\frac{\%Item_{blend\,measured} - \%Item_{DF\,measured}}{\%Item_{DF\,measured}}\right]*100$$

Item (CO, CO_2, NO_X, HC and O_2), at the same load

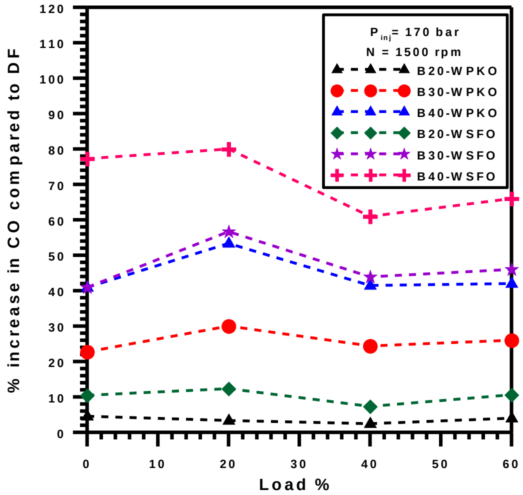

Figure (A.1): %age. increase in CO compared to DF

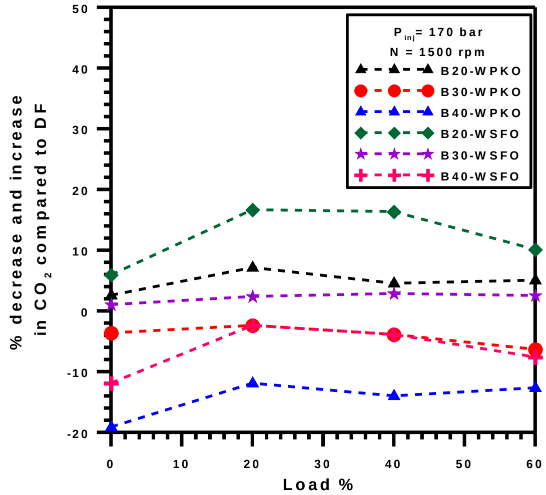

Figure (A.2): %age. increase and decrease in CO_2 compared to DF

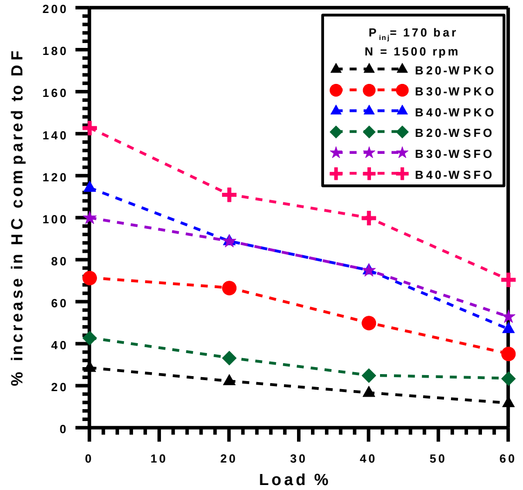

Figure (A.3): %age. increase in HC compared to DF

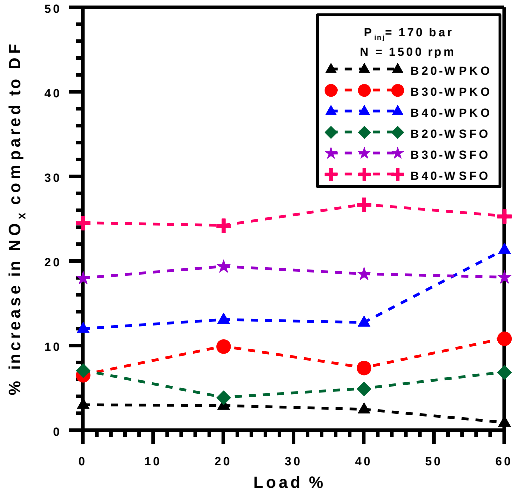

Figure (A.4): %age. increase in NO_X compared to DF

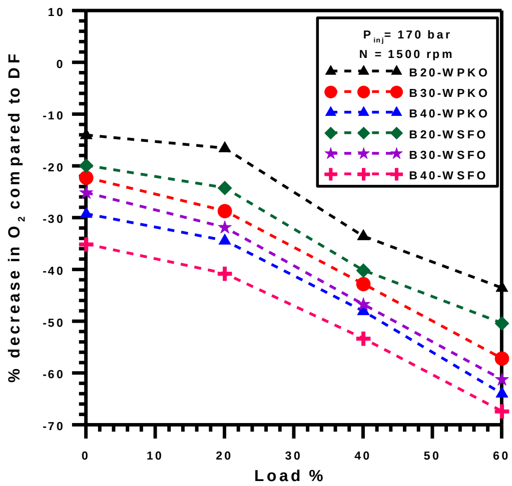

Figure (A.5): %age. decrease in O_2 compared to DF

تحقيق تجريبي لانبعاثات محرك ديزل باستخدام خلطات من الزيوت النباتية المبددة

ملخص باللغة العربية

في الوقت الحاضر تمثل أزمة الطاقة والمناخ وتلوث الهواء مشاكل عالمية كبرى بالإضافة إلى ارتفاع أسعار الوقود الأحفوري والزيوت النباتية. وقد تفاقمت هذه المشاكل مع الصراعات العالمية الحالية التي أدت إلى زيادة الاحتباس الحراري وارتفاع درجات الحرارة العالمية مما تسبب في تغير مناخي كبير في العديد من مناطق العالم. يعد انبعاث ثاني أكسيد الكربون أحد الملوثات الرئيسية التي تسبب زيادة الاحتباس الحراري. لهذا يمكن استخدام الزيوت النباتية المبددة مباشرة كوقود بديل في محركات الديزل لأنها صديقة للبيئة.

في هذا البحث تم دراسة تأثير استخدام الزيوت النباتية المبددة بنسب خلط مختلفة على انبعاثات محرك ديزل ومقارنتها بوقود الديزل النقي. ومن النتائج المهمة لهذا البحث أنه مع زيادة نسبة الزيوت النباتية المبددة في الخليط (الوقود)؛ يؤدي إلى انخفاض في انبعاثات ثاني أكسيد الكربون. تزداد انبعاثات ثاني أكسيد الكربون بنسبة ٥٪ و ١٠,١٣٪ لوقود B20-WPKO و B20-WSFO على التوالي مقارنة بوقود الديزل النقي عند ٦٠٪ من الحمل، و تنخفض انبعاثات ثاني أكسيد الكربون بنسبة ١٢,٦٦٪ و ٧,٦٪ لوقود B40-WPKO و B40-WSFO على التوالي مقارنة بوقود الديزل النقي عند ٦٠٪ من الحمل. أدى استخدام هذه الزيوت إلى مزيد من الانخفاض في انبعاثات ثاني أكسيد الكربون، وبالتالي انخفاض في ظاهرة الاحتباس الحراري، علاوة على ذلك، فإن معالجة هذه الزيوت وإعادة استخدامها ضار بصحة الإنسان.