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Original Research

Effect of Waste Cooking Oil Blending with Diesel Fuel on Tractor Engine Performances and Exhaust Gases Emission

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Abstract

A significant amount of waste cooking oil (WCO) remains in the food preparation process worldwide on a daily basis, which can cause environmental pollution if disposed of improperly. The cheapest and effective way to dispose of WCO is by blending it with diesel fuel. In this study three various blends of WCO and diesel fuel were prepared with a WCO proportion of 10%, 20% and 30% and properties were evaluated and compared with petroleum diesel fuel. The density and dynamic viscosity of the blend increase with the increase in WCO content, while the heating value decreases. The blends were then tested in tractor direct injection diesel engine to determine the effect of blending WCO with diesel fuel on the engine performances (power, torque and fuel consumption) and exhaust gases emission (CO, CO_2, HC and NO_x). The results show that the engine performances using WCO blends are comparable to petroleum diesel fuel and a blend with 30% WCO (B30) achieved the best results among the fuel blends. There were no significant differences in average engine power, torque and fuel consumption per hour between petroleum diesel fuel and B30 blend, while significantly lower ($P<0.05$) average specific fuel consumption were achieved using diesel fuel. The significantly lower ($P<0.05$) average CO and CO_2 emissions and significantly higher ($P<0.05$) average HC emission was achieved using diesel fuel compared to B30 blend. No significant difference in average NO_x emission was observed between diesel fuel and B30 blend.

Keywords: waste cooking oil, diesel fuel, engine performances, fuel consumption, emission

Introduction

Increased consumption of liquid fossil fuels and rising fuel prices with constant demands to reduce environmental pollution from the exhaust gases of internal combustion engines are leading to an intensified search for alternative solutions, especially to replace diesel fuel, which plays a significant role as fuel for diesel engines in transport vehicles and in a wide range of mobile machinery used in construction, agriculture and many other industrial activities. Diesel engines were reported as one major mobile emission sources of pollutants, including carbon monoxide (CO), total hydrocarbons (HC), nitrogen oxides (NOx),

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and particulate matter (PM) [1]. Together with the development of high conversion efficiency diesel engines, cost-effective after treatment technologies and advanced clean combustion concepts, using cleaner alternative fuels is one of the focuses of pollutant reduction techniques [2]. In the last few decades, alternative fuels have been investigated for partial or total replacement of diesel fuel for reducing air pollution and reducing reliance on fossil fuels [3]. Vegetable oils have been identified as a promising alternative source to replace fossil fuels in compression-ignition engines because they are renewable and similar in their characteristics to diesel fuel [4]. However, vegetable oils still have significantly higher prices compared to petroleum diesel fuel. Furthermore, the use of edible vegetable oils as fuel might lead to problems with the food supply and may cause greater greenhouse gas emissions due to the direct land-use impact and indirect impacts, such as deforestation [2, 5]. Because of these reasons, using waste cooking oil (WCO) as fuel for diesel engine can be considered as a more economical and sustainable solution [6].

Large quantities of WCO are available throughout the world. The amount of WCO generated from every country worldwide is huge and varies accordingly to the amount of cooking oil consumed [7]. Annually, a total of more than 15 million tonnes of WCO is generated from selected countries in the world such as in China (4.5 million tonnes/year), Malaysia (0.5 million tonnes/year), United States (10.0 million tonnes/year), Taiwan (0.07 million tonnes/year), European (0.7-1.0 million tonnes/year), Canada (0.12 million tonnes/year) and Japan (0.45-0.57 million tonnes/year) [8]. Croatia is a tourist-oriented country and many hotels, restaurants and fast food shops generate a significant amount of WCO every day, especially during the tourist season. Because continued consumption of WCO for food preparation is dangerous to human health and increases the risk of cardiovascular diseases, liver problem and cancer, the most of the used cooking oil is poured into the sewer system of the cities or directly into water bodies or on the soil surfaces. This practice contributes to the pollution of rivers, lakes, seas and underground water, which is very harmful for environment and human health [9]. Waste cooking oil collection and recycling programme is among the most common practice in developed countries or regions like the United States, Japan and EU [10]. The project of collecting WCO from households in Croatia was launched in 2017, while all caterers have a legal obligation to the disposal of waste oil. The use of WCO as fuel for diesel engines presents the best means of disposal and can encourage collection and reduce illegal dumping [11, 12]. Recycling WCO as an alternative fuel for diesel engines also presents a promising avenue to reduce dependency on depleting fossil oil reserves [13].

Like other vegetable oils, due to the different physical and chemical properties of WCO compared to those of petroleum diesel fuel, direct use in diesel engines leads to some problems such as the formation of carbon deposit in the combustion chamber, incomplete combustion and some problems such as clogging injector and sticking piston ring, mainly because of the high viscosity and low volatility [14]. These problems can be avoided by subjecting WCO to a transesterification process to obtain biodiesel because transesterification is an effective method of reducing vegetable oil viscosity and eliminating operational and durability problems of diesel engine [15]. However, transesterification is a time consuming, complex and expensive process that also produces glycerol as a by-product which has to be again disposed of carefully [16, 17]. So, the cheapest way to use WCO as fuel is by adding it to the petroleum diesel fuel and such a way of WCO disposal is economically more rewarding and ecologically more sustainable than convert it to biodiesel, just need to determine in which proportion. The aim of this study was to investigate the effects of different proportions of WCO in diesel fuel blends (with 10%, 20% and 30% WCO) on diesel engine performances and exhaust emissions at different engine loads.

Material and Methods

Experimental Setup

The experiment with different WCO-diesel fuel blends was carried out using a four-cylinder diesel engine made in tractor factory Torpedo under license Deutz and installed in tractor Torpedo D 6806. An engine that does not meet the newer Stage I-V exhaust emissions standards was chosen because the impact of WCO blends consumption on all engine components of new generation tractor engines has not yet been sufficiently investigated. The rated engine power declared by the manufacturer is 49 kW at 2200 rpm

Table 1. Technical characteristics of the tested diesel engine.

Engine type	Four stroke diesel
Engine model	F4L 912
Fuel injection system	Direct injection
Aspiration system	Atmospheric
Cooling system	Air cooling
Bore	100 mm
Stroke	120 mm
Displacement	3768 cm3
Compression ratio	17:1
Valves per cylinder	2
Fuel injection pump	Conventional in-line pump
Fuel injection pressure	175 bar

and the maximum torque is 221 Nm at 1600 rpm. Technical characteristics of the tested engine are shown in Table 1.

The experiment was conducted at Laboratory for testing tractors and engines (University of Zagreb, Faculty of Agriculture, Agricultural Engineering Department). During the testing of the engine performances with different fuels, engine load, engine speed and fuel consumption per hour were measured. The diesel engine was connected through the tractor power take-off shaft to the hydraulic dynamometer Schenk type U1-40 (accuracy level <1%) and the different engine load was realized by dynamometer braking force changing. Engine speed was measured using a Lutron DT 2236 digital speed meter (accuracy ±0.05%), and fuel consumption per hour was measured by the volumetric method using a 100 ml belly pipette. From the obtained data, the values for engine power and torque, as well as specific fuel consumption, were calculated. Data on environmental conditions (temperature, relative humidity and air pressure) come from the meteorological station of the Croatian Meteorological and Hydrological Service Zagreb-Maksimir, which is located near the laboratory where the experiment was conducted. The average temperature during the experiment was 15.2ºC, relative humidity 56.0% and air pressure 1019.2 hPa.

Since the experiment was conducted on a tractor diesel engine, the engine performances using different fuels were evaluated in compliance with the OECD standard for the purpose of the official testing of agricultural tractors [18]. The testing first included 6 points in the area of the governor control with full load. Point 1 represents the rated power, point 2 is the power at a torque of 85% which is achieved in point 1, points 3, 4, 5 are the powers at a torque of 75%, 50% and 25% achieved in the point 2, respectively, while point 6 represents the performances of unloaded engine. Further measurements were made in the range from rated power to maximum torque measured at every 200 rpm (between 1200 and 2000 rpm).

The analysis of exhaust gases of diesel engine was carried out at different engine loads between 10% and 100% [15]. Exhaust gas analysis was performed with a MAHA MET 6.3 analyser (MAHA Maschinenbau Haldenwang GmbH & Co. KG., Haldenwang, Germany) and include CO, CO_2, HC, and NO_x gases analysis. Measurement characteristics of used exhaust gas analyser Maha MET 6.3 are shown in Table 2.

Fuel Properties

In this experiment, petroleum diesel fuel purchased at the nearest petrol station under the name Eurodiesel was used. This diesel fuel meets the valid European standard EN 590 in all quality requirements and application properties, and is compatible with the used tractor engine. WCO was collected from student restaurant of Faculty of Agriculture in Zagreb, which uses sunflower edible oil for food preparation. Before blending with diesel fuel, the WCO has been filtered to remove food residues and solid precipitate in the oil. Four test fuels were used in this study, including 100% petroleum diesel fuel (D100) as the reference fuel, and the other fuels were blends between WCO and diesel fuel with various WCO proportions, i.e. blend of 10% WCO and 90% diesel fuel (B10), 20% WCO and 80% diesel fuel (B20), and 30% WCO and 70% diesel fuel (B30). Properties of diesel fuel and WCO-diesel fuel blends were determined in a licensed testing laboratory according to standard ASTM methods. After preparing the blends, the fuel tank was filled with the blend to be tested and the engine was run for a certain time without recording data so that all the fuel remaining from the previous test was consumed and the entire fuel supply system was filled with the new fuel. This procedure was repeated for each fuel blend. The tests were repeated three times for every fuel in order to increase the reliability of the test results.

The properties of diesel fuel and WCO-diesel fuel blends were determined according to standard ASTM methods and the results are shown in Table 3. The tested fuels were 100% petroleum diesel fuel (D100) and blends between WCO and diesel fuel with various WCO proportions, i.e. blend of 10% WCO and 90% diesel fuel (B10), 20% WCO and 80% diesel fuel (B20), and 30% WCO and 70% diesel fuel (B30).

The obtained results show that the density and dynamic viscosity of the blend increase with the increase in WCO content, while the heating value decreases. Increasing of fuel density and viscosity and decreasing of heating value with the increase of WCO

Table 2. Measurement characteristics of exhaust gas analyser Maha MET 6.3.

Exhaust gases	CO	CO_2	HC	NO_x
Measuring range	0-15% Vol.	0-20% Vol.	0-30000 ppm	0-5000 ppm
Measurement accuracy	0.03% Vol.	0.5% Vol.	8 ppm	32-120 ppm
Measured value resolution	0.01% Vol.	0.01% Vol.	1 ppm	1 ppm
Measuring principle	Infrared spectrometry (NDIR)	Infrared spectrometry (NDIR)	Infrared spectrometry (NDIR)	Electrochemical detection

*Nondispersive infrared sensor

Table 3. Comparison of the tested fuels properties.

Property	Testing method	D100	B10	B20	B30
Density at 15ºC (kg/dm³)	ASTM D 4052	0.832	0.844	0.852	0.859
Dynamic viscosity at 40ºC (mPa.s)	ASTM D 7042	2.018	2.597	3.3489	4.437
Heating value (MJ/kg)	ASTM D 240	44.58	44.10	43.56	42.97
Flash point (ºC)	ASTM D 975	60	62	65	68
Pour point (ºC)	ASTM D 5950	-24	-15	-10	-8
Cloud point (ºC)	ASTM D 2500	-5	-5	-4	-4
Filterability limit (ºC)	ASTM D 6426	-18	-16	-15	-14

proportion in WCO diesel fuel blend was also reported by [8, 19]. The increase of WCO proportion in blend is positively correlated with all measured temperature points (flash, pour and cloud) and filterability limit.

Statistical Analysis

Statistical analysis was done applying the analysis of variance (ANOVA) with t-test conducted to verify the significance of diference ($P<0.05$) in arithmetic mean values of the measured variables. The analysis of variance was also performed to determine if there was any deterioration of engine performances (power, torque and fuel consumption) throughout the testing period.

Results and Discussion

Diesel Engine Performances

The testing of diesel engine performances with four different fuels was carried out at different engine speeds and load conditions and the results are shown in Figs 1-4. Fig. 1 shows the achieved engine power when using four different types of fuel. The maximum engine power with all fuels was achieved at 2200 rpm. The highest engine power achieved with D100 fuel was 43.16 kW, while slightly lower power of 43.00 kW was achieved with fuel blend B30. Maximum engine power achieved with fuel blends B10 and B20 were significantly lower ($P<0.05$) with 41.51 kW and 41.18 kW, respectively. The highest power in the area from rated power to maximum torque were achieved using fuel blend B30 and the lowest using fuel blend B20. If the average results of all measurements are compared, there were no significant differences ($P<0.05$) in engine power between D100 fuel and B10 and B30 blends, while using B20 blend significantly lower ($P<0.05$) average engine power was achieved. Isa Ali et al. [8] reported that fuel blends with 10-30% WCO and 90-70% diesel fuel even produced higher engine power than conventional diesel fuel and these results are explained by slightly larger drops of fuel and oxygen contained in fuel blends that contribute to better atomization. On the contrary, [20, 21] observed that the percentage addition of the WCO biodiesel in the fuel blend has a tendency to reduce the power at each change in load and this is related to the heating value and cetane number of the WCO biodiesel, which are lower than of the fossil diesel fuel. According to [19], this is compensated by the higher density of WCO and increased quantity of injected fuel when higher percentage of WCO is applied.

Fig. 2 shows the engine torque achieved with using four different fuels. At all engine speeds using D100 fuel and B30 blend similar results were achieved, but the highest torque was achieved using D100 fuel with 204.41 Nm at 1400 rpm. The lowest torque values at all measurement points and significantly lower ($P<0.05$) average engine torque were achieved using a B20 blend, while between other fuels there were no significant differences ($P<0.05$) in engine torque. Chiatti et al. [22] showed the variation of engine torque with speed at full-load condition for diesel fuel and blends with 20% and 40% WCO and concluded that the torque trend at full-load condition depends on the proportion of WCO in the fuel; since WCO has a lowering heating value than diesel fuel. With that are agree [20], with additional opinion that high engine torque with pure diesel is due to the fact that the density of WCO blend is higher than that of the pure diesel fuel, therefore a larger mass flow

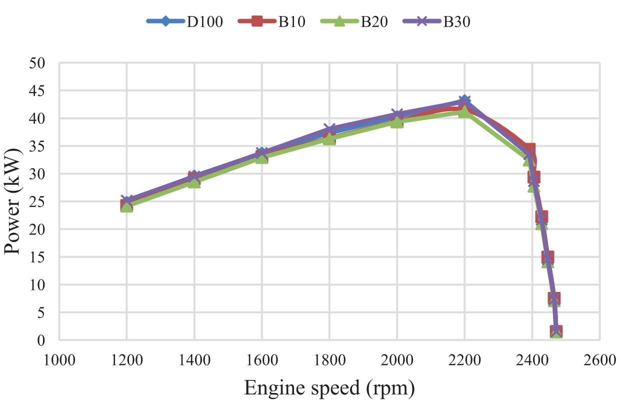

Fig. 1. Engine power vs. engine speed with using four different fuels.

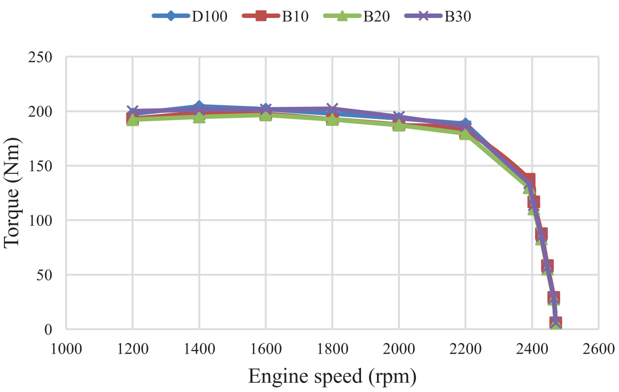

Fig. 2. Engine torque vs. engine speed with using four different fuels.

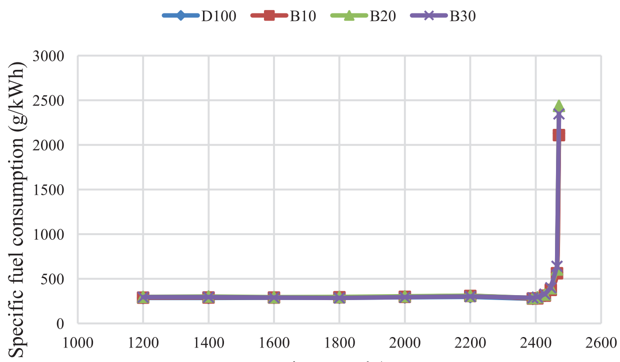

Fig. 4. Specific fuel consumption vs. engine speed with using four different fuels.

rate for the same fuel volume is pumped to the engine, resulting in an increase in torque. According to [19], at low engine speeds engine torque increases with the higher proportion of WCO, while at high engine speeds the modified operation of a mechanical governor is observed and the governor starts to reduce injected fuel quantity earlier when the higher proportion of WCO is used and engine torque decrease faster.

Fig. 3 shows fuel consumption per hour of diesel engine when using four types of fuel. Differences in fuel consumption per hour when using four types of fuel were minimal, but the highest fuel consumption per hour of 15.63 kg/h was recorded using D100 fuel at 2204 rpm. The lowest fuel consumption per hour was recording using B20 blend at most measuring points, but there were no significant differences ($P<0.05$) in consumption per hour between tested fuels. Opposite of that, [23] reported that under the same engine operation conditions B10 blend has higher fuel consumption per hour in all measured points. Varun and Harish [24] reported that diesel engine consumed slightly more WCO biodiesel per hour in comparison to conventional diesel fuel. In our study the highest consumption with all fuels were measured at maximum engine power. Maksum et al. [20] indicated that fuel consumption increased at higher engine loads due to the higher amount of fuel required to produce more engine power.

Fig. 4 shows the specific fuel consumption with four types of fuel. The lowest specific fuel consumption was achieved using D100 fuel with 276.28 g/kWh at 2391 rpm. The biggest differences between the results are visible at engine maximal speed in this measurement. The significantly lower ($P<0.05$) average specific fuel consumption was achieved using D100 fuel and B10 blend compared to B20 and B30 blends. Chiatti et al. [22] reported that the specific fuel consumption increases with the content of WCO in the fuel and the average increase over all engine speed values is 3.9% for B20 and 7.1% for B40 blend, while [23] reported even 11.69% higher specific fuel consumption of B20 blend than D100 diesel fuel. According to [8], the differences in specific fuel consumption may be a consequence of the higher density and lower calorific value of the blended fuels compared to diesel fuel. Meng et al. [25] reported that specific fuel consumption decreased with increasing in load and explanation for this reduction could be due to the higher percentage of increase in engine power with load as compared to fuel consumption.

Exhaust Gases Analysis

The results of the analysis of exhaust gases emitted by diesel engine at different loads when using four different fuels are shown in Figs 5-8. Fig. 5 shows carbon monoxide emission as function of the engine load with four different fuels. The lowest oscillations in the CO emission were observed with D100 fuel while the highest oscillations were observed with B20 blend and with this blend was achieved the lowest CO emission of 0.03% at 75% engine load. The significantly lower ($P<0.05$) average CO emission was achieved using D100 fuel compared to all three blends. The largest differences between used fuels were observed at the engine full load, and the lowest CO emission was achieved using D100 fuel, while the highest of 0.14% was achieved using B20 blend. A significant increase

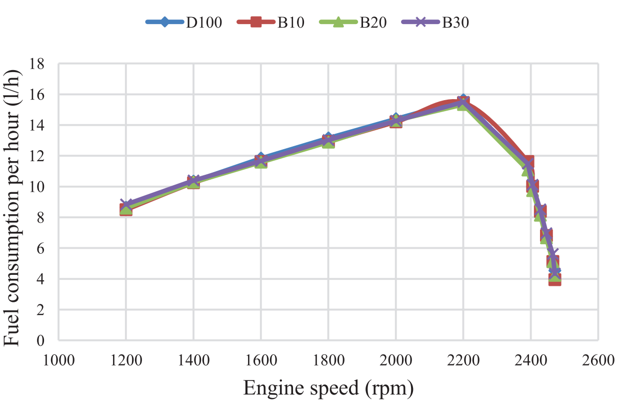

Fig. 3. Fuel consumption per hour vs. engine speed with using four different fuels.

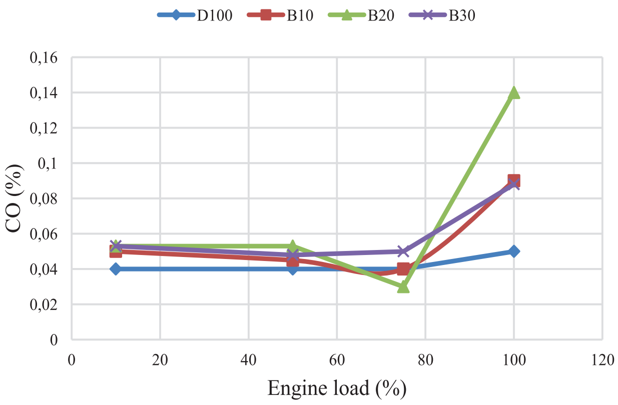

Fig. 5. Carbon monoxide emission vs. engine load with using four different fuels.

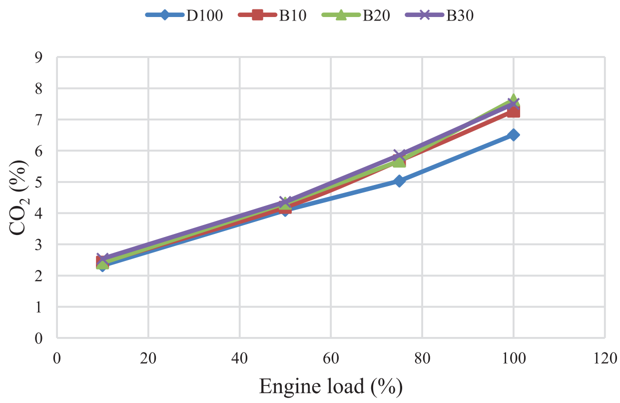

Fig. 6. Carbon dioxide emission vs. engine load with using four different fuels.

of CO emission at full load was observed using all three blends, which was also observed by [24, 26]. The higher CO emission of diesel fuel blended with WCO in comparison to pure diesel fuel was also reported by [8] and their explanation for it is the high viscosity of WCO, which causes poor spray characteristics, forming locally rich air-fuel mixtures during the combustion process leading to CO formation during the combustion, due to the lack of oxygen locally. On the contrary, [15] stated that CO emission reduces with increase in percentage of WCO in the fuel blends and concluded that decreases in carbon monoxide emission for biodiesel blends were due to more oxygen molecules and lower carbon content in WCO blends as compared to diesel fuel which lead to better combustion. Yildizhan et al. [27] reported that increasing of compression ratio decreased CO emission for all test fuels due to better combustion of fuels.

Fig. 6 shows emission of the carbon dioxide at different engine load using four types of fuel. It is evident that CO_2 emission is directly proportional to the load and as the load increases so does CO_2 emission increase significantly. The same trend of CO_2 emission has been also observed by some other authors [8, 24, 25]. Abed et al. [15] have also noticed this trend and attribute it due to the higher fuel entry as the load increased. The significantly lower ($P<0.05$) average CO_2 emission was achieved using D100 fuel compared to all three blends. At lower loads there were small differences in CO_2 emission between used fuels and the lowest CO_2 emission of 2.32% was achieved at 10% engine load with D100 fuel. At full load significantly lower CO_2 emission was achieved using D100 fuel in comparison to all three blended fuels. The lower CO_2 emission of pure diesel fuel than those blended with WCO was also reported by [15, 23, 24], according to which the reason for higher CO_2 emission of WCO blends compared to pure diesel fuel is a higher carbon-to-hydrogen ratio and the existence of oxygen in the molecular structure. The lower CO_2 emission of diesel fuel blended with WCO were reported by [8, 28] and as a reason for that they considered relatively lower carbon content in the same volume of fuel consumed at the same engine load.

Fig. 7 shows the hydrocarbon emissions achieved when using four types of fuel. The lowest HC emission of 21.75 ppm was achieved with B20 blend at 75% engine load. At lower loads were observed significantly lower HC emissions using B20 and B30 blends in comparison to D100 and B10 fuels, but at full load the lowest HC emission was achieved using D100 fuel and with this fuel the lowest oscillations in HC emission with engine load changes were observed. The significantly lower ($P<0.05$) average HC emission was achieved using B20 and B30 blends compared to D100 fuel and B10 blend. The lower HC emission at engine part load and increases with increase of engine load was also observed by [15, 24], who state this is due to the presence of fuel rich mixture and lack of oxygen resulting from engine operation. The higher oxygen content of WCO leads to better combustion resulting in lower emission of HC and the major factor for large difference of HC emission is lower volatility of WCO compared with diesel [29]. On the contrary, [30] state as the percentage of WCO in blend with diesel fuel raises, HC emission also increase when compared with pure diesel fuel operation.

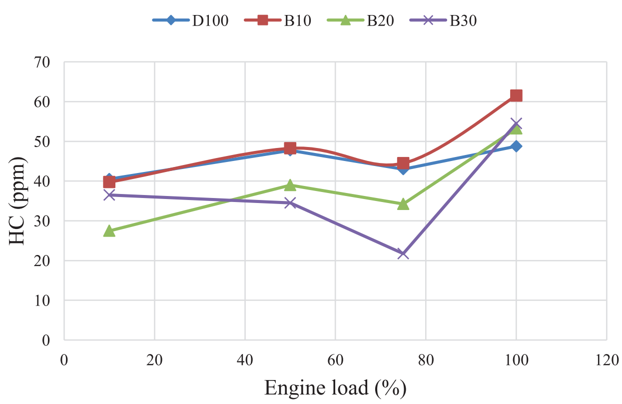

Fig. 7. Hydrocarbon emission vs. engine load with using four different fuels.

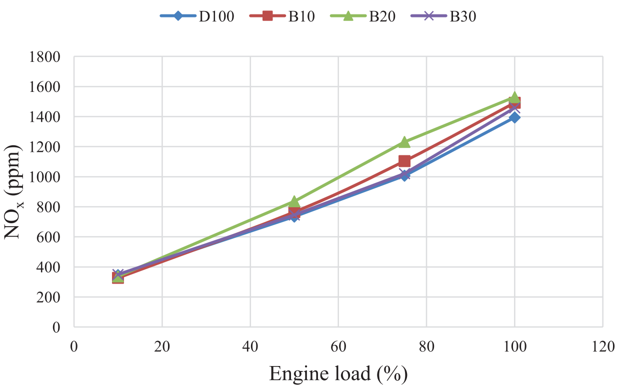

Fig. 8. Nitrogen oxides emission vs. engine load with using four different fuels.

Fig. 8 shows emission of the nitrogen oxides at different engine load using four types of fuel and it is evident that NO_x emission increases significantly with increasing engine load. The same NO_x emission trend was also reported by [23, 28, 31]. At load of 10% there were minimal differences in NO_x emission between used fuels and the lowest NO_x emission of 327.50 ppm was achieved with B10 blend. The significantly lower ($P<0.05$) average NO_x emission was achieved using D100 fuel and B30 blend compared to B10 and B20 blends. The greater differences in NO_x emission were observed at higher loads and the highest values were achieved with B20 blend, while the lowest were achieved with D100 fuel. The lower NO_x emission of pure diesel fuel than diesel fuel blended with WCO was also reported by [15, 23, 27], who explain that increase in NO_x emission for WCO blends was due to increase of oxygen content in blends and higher cylinder temperature compared to diesel fuel. In addition to the effect of temperature, the increase in NO_x emission can be explained by considering the differences in fuel chemistry, spray properties, and ignition delay that affect the duration of premixed and diffusion burn regimes [22]. On the contrary, [25, 28] reported lower NO_x emission of WCO blends and attributed this with lower temperature in the combustion chamber temperatures a reason for that they considered relatively lower carbon content in the same volume of fuel consumed at the same engine load.

Based on the results obtained in this study, as well as the results of other authors, can be concluded that engine performances and exhaust emissions of diesel engine depend not only on the type of fuel but also on the engine technical characteristics such as compression ratio [26], fuel injection system [22], ignition type [12, 16], injection pressure [30], as well as the engine operating mode (load and speed).

Conclusions

Based on the obtained results in this study, it can be concluded that the use of WCO and diesel blend for tractor diesel engines is possible. The results show that tractor engine performances using WCO and diesel fuel blends are comparable to that when using pure diesel fuel. Among the tested blends with different WCO proportion, the best results were achieved using B30 blend. There were no significant differences ($P<0.05$) in average engine power, torque and fuel consumption per hour between D100 fuel and B30 blend, but significantly ($P<0.05$) lower specific fuel consumption were achieved using D100 fuel.

In this study, it was found that the emission of exhaust gases directly depends on the engine load, and a significant increase in emissions with increasing load was observed for all measured gases. The significantly lower ($P<0.05$) average CO and CO_2 emissions were achieved using D100 fuel compared to all three blends, while significantly lower ($P<0.05$) average HC emission was achieved using B20 and B30 blends compared to D100 fuel. The significantly lower ($P<0.05$) average NO_x emission was achieved using D100 fuel and B30 blend compared to B10 and B20 blends, so according to the emission of exhaust gases, among blends the best results were also achieved using B30 blend.

The results observed in this study indicate the good potential of using WCO and diesel blends as alternative fuels for diesel engines and encourage further research with even a higher proportion of WCO in blend with diesel fuel. Because this study was conducted with an engine that does not meet the newer Stage I-V exhaust emissions standards, additional research is needed to determine the impact of the WCO and diesel fuel blends on the new generation of tractor engines. Blending of WCO with diesel fuel can be also a suitable technique for efficient and cheap disposal of WCO.

Conflict of Interest

The authors declare no conflict of interes.

References

1. REDFERN F.M., LIN S.L., WANG L.C., SHIH S.I. Influences of waste cooking oil-based biodiesel blends on PAH and PCDD/F emissions from diesel engines in durability testing cycle. Aerosol Air Qual. Res. **17** (5), 1224, **2017**.
2. CHANG Y.C., LEE W.J., WANG L.C., YANG H.H., CHENG M.T., LU J.H., TSAI Y.I., YOUNG L.H. Effects of waste cooking oil-based biodiesel on the toxic organic pollutant emissions from a diesel engine. Appl. Energy **113**, 631, **2014**.
3. MAN X.J., CHEUNG C.S., NING Z., YUNG K.F. Effect of waste cooking oil biodiesel on the properties of particulate from a DI diesel engine. Aerosol Sci. Technol. **49** (4), 199, **2015**.
4. DABI M., SAHA U.K. Application potential of vegetable oils as alternative to diesel fuels in compression ignition engines: A review. J. Energy Inst. **92** (6), 1710, **2019**.

5. FARGIONE J., HILL J., TILMAN D., POLASKY S., HAWTHORNE P. Land clearing and the biofuel carbon debt. Science **319** (5867), 1235, **2008**.
6. FEREIDOONI L., TAHVILDARI K., MEHRPOOYA M. Trans-esterification of waste cooking oil with methanol by electrolysis process using KOH. Renew. Energy **116** (A), 183, **2018**.
7. GUI M.M., LEE K.T., BHATIA S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy **33** (11), 1646, **2008**.
8. ISA ALI M., SHAHRIR A., FAIZAL W.M., ISKANDAR M.T. The use of untreated waste cooking oil and diesel fuel blends as IC engine fuels. Appl. Mech. Mater. **699**, 708, **2014**.
9. ABU-JRAI A., YAMIN J.A., AL-MUHTASEB A.H., HARARAH M.A. Combustion characteristics and engine emissions of a diesel engine fueled with diesel and treated waste cooking oil blends. Chem. Eng. J. **172**, 129, **2011**.
10. PATEL M.J., PATEL T.M., RATHOD G.R. Performance analyis of C.I. engine using diesel and waste cooking oil blend. IOSR J. Mech. Civ. Eng. **12** (2), 27, **2015**.
11. BARI S., YU C.W., LIM T.H. Effect of fuel injection timing with waste cooking oil as a fuel in a direct injection diesel engine. Proc. Instn. Mech. Engrs. Part D: J. Aut. Eng. **218** (1), 93, **2004**.
12. NGUYEN T.V., NGUYEN K.D., HO N.X., NGUYEN V.D. Engine performance and combustion characteristics of a direct injection compression ignition engine fueled waste cooking oil synthetic diesel. Int. J. Coal. Sci. Technol. **7** (3), 560, **2020**.
13. KRISHNAMOORTHY V., DHANASEKARAN R., RANA D., SARAVANAN S., RAJESH KUMAR B. A comparative assessment of ternary blends of three bio-alcohols with waste cooking oil and diesel for optimum emissions and performance in a CI engine using response surface methodology. Energy Convers. Manag. **156**, 337, **2018**.
14. MAT S.C., IDROAS M.Y., HAMID M.F., ZAINAL Z.A. Performance and emissions of straight vegetable oils and its blends as a fuel in diesel engine: A review. Renew. Sust. Energ. Rev. **82** (1), 808, **2018**.
15. ABED K.A., EL MORSI A.K., SAYED M.M., EL SHAIB A.A., GAD M.S. Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. Egypt. J. Pet. **27** (4), 985, **2018**.
16. KALAM M.A., MASJUKI H.H., JAYED M.H., LIAQUAT A.M. Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. Energy **36** (1), 397, **2011**.
17. KUMAR M.S., JAIKUMAR M. A comprehensive study on performance, emission and combustion behaviour of a compression ignition engine fuelled with WCO (waste cooking oil) emulsion as fuel. J. Energy Inst. **87** (3), 263, **2014**.
18. OECD. Standard code for the official testing of agricultural and forestry tractor performance. Code 2. Organisation for Economic Co-operation and Development, Paris, **2022**.
19. HRIBERNIK A., KEGL B. Performance and exhaust emissions of an indirect-injection (IDI) diesel engine when using waste cooking oil as fuel. Energy Fuels **23** (3), 1754, **2009**.
20. MAKSUM H., PURWANTO W., PULUNGAN A.B. The effect of waste cooking oil biodiesel to the diesel engine performance. Int. J. GEOMATE **17** (64), 245, **2019**.
21. OYEDEPO S.O., AIRHIHEN P.I., ADELEKAN D.S., OHIJEAGBON O.I., KELVIN E.U., DIRISU J.O., UDO M.O. Experimental investigation of waste vegetable oil - diesel fuel blends effects on performance of compression ignition engine. Procedia Manuf. **35**, 1039, **2019**.
22. CHIATTI G., CHIAVOLA O., RECCO E. Effect of waste cooking oil biodiesel blends on performance and emissions from a CRDI diesel engine. In: Ceper B.A. (ed.), Improvement trends for internal combustion engines. IntechOpen, London, 19, **2018**.
23. WU G., JIANG G.H., YANG Z.Y., HUANG Z.J. Emission characteristics for waste cooking oil biodiesel blend in a marine diesel propulsion engine. Pol. J. Environ. Stud. **28** (3), 2911, **2019**.
24. VARUN K.R., HARISH G. Comparative study of waste cooking oil with diesel for performance and emission analysis. J. Emerg. Technol. Innov. Res. **8** (10), 111, **2021**.
25. MENG X.M., CHEN G.Y., WANG Y.H. Biodiesel production from waste cooking oil via alkali catalyst and its engine test. Fuel Process. Technol. **89** (9), 851, **2008**.
26. ULUSOY Y., ARSLAN R., TEKIN Y., SURMEN A., BOLAT A., SAHIN R. Investigation of performance and emission characteristics of waste cooking oil as biodiesel in a diesel engine. Pet. Sci. **15** (2), 396, **2018**.
27. YILDIZHAN S., ULUDAMAR E., CALIK A., DEDE G., OZCANLI M. Fuel properties, performance and emission characterization of waste cooking oil (WCO) in a variable compression ratio (VCR) diesel engine. Eur. Mech. Sci. **1** (2), 56, **2017**.
28. ZAREH P., ZARE A.A., GHOBADIAN B. Comparative assessment of performance and emission characteristics of castor, coconut and waste cooking based biodiesel as fuel in a diesel engine. Energy **139**, 883, **2017**.
29. KALIVEER V., SEQUEIRA P.R., D'SA R.V., DSILVA S.A., SANDEEP B., D'SILVA R.S. Investigation on the performance and emissions characteristics of CI engine using different blends of waste cooking oil methyl ester-ethanol-diesel oil. Energy Power **6** (1A), 28, **2016**.
30. AL-GHAFIS A., BASHA M.S. Experimental trails on diesel engine performance and emission characteristics of waste cooking oil combinations at varying injection pressures. Am. J. Appl. Sci. **18** (1), 15, **2021**.
31. CHAURASIYA P.K., SINGH S.K., DWIVEDI R., CHOUDRI R.V. Combustion and emission characteristics of diesel fuel blended with raw jatropha, soybean and waste cooking oils. Heliyon **5** (5), e01564, **2019**.