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The performance of a developed diesel vehicle to run on WCO biodiesel at variable speeds and loads

Abstract: Vehicle emissions and performance fueled with waste cooking oil biodiesel is the main topic of this research. Biodiesel was produced through transesterification with physical and chemical characteristics comparable to diesel. B20 is a methyl ester of 20% blended with diesel. A diesel vehicle was modified and equipped with all measuring instruments needed to perform all experiments. The variable speed and load tests were conducted on the vehicle to measure the performance and emissions at different loads (0–30 kW) and different speeds (0–33 km/h). The vehicle speed was the maximum attained for each gear with a constant fuel flow rate without external fuel control at a steady state. At a vehicle speed of 33 km/h, the greatest increases in fuel consumption and exhaust gas temperature for biodiesel B20 were 17 and 6%, respectively, as related to pure diesel. At a vehicle speed of 33 km/h, B20 reduced the distance traveled, carbon monoxide and hydrocarbon concentrations compared to diesel by 22, 9 and 10%, respectively. At a vehicle speed of 33 km/h, the increases in nitrogen oxides and oxygen concentrations of B20 were 4 and 3% higher, respec-

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tively, than crude diesel over the whole tested load range. The biggest increases in distance, fuel consumption, and exhaust gas temperature for B20 over diesel were 13, 3, and 2%, respectively, at a vehicle load of 30 kW. The B20 blend decreased CO and hydrocarbon emissions related to diesel by 17 and 32%, respectively, at a vehicle load of 30 kW. The increases in nitrogen oxides and oxygen concentrations of B20 across the whole load range were 11 and 3% higher than pure diesel at a vehicle load of 30 kW, respectively. Biodiesel blend B20 is suggested for application in vehicles providing that the vehicle is moderately loaded.

KEYWORDS: WCO, biodiesel, vehicle, variable load, variable speed

Nomenclature and abbreviations

ASTM	–	American Society of Testing and Materials
B20	–	biodiesel of 20% volume percentage blending with diesel oil
CO	–	carbon monoxide emission [%]
D100	–	pure diesel oil
EGT	–	exhaust gas temperature [°C]
HC	–	hydrocarbon emission [ppm]
VS	–	variable speed
VL	–	variable load
WCO	–	waste cooking oil

Introduction

Environmental issues and lack of fuel supplies mean that it is an appropriate time to look into acceptable sustainable alternative fuels (Altun et al. 2011; Hasanin et al. 2022; Ibrahim S.M.A. et al. 2017; Khalaf et al. 2023; Khater et al. 2023). Most research has concentrated on non-edible vegetable oils to produce biodiesel due to edible vegetable oils being costly (Galushchak et al. 2023; Ibrahim M.M. et al. 2022; Koh and Tinia 2011; Shah et al. 2004). A promising alternative to hydrocarbon diesel fuel is the green methyl ester fuel (Khater et al. 2024; Kumar and Sharma 2008; Kupchuk et al. 2022; Shah et al. 2005).

The brake thermal efficiency (BTE) of engines utilizing methyl-diesel mixtures is reduced as the fraction of biodiesel increases, owing to the lower calorific value of methyl esters (Mohamed et al. 2022; Ramesh 2016; Rao et al. 2007; Suresh et al. 2012). Biodiesel is less thermally efficient than pure diesel because of its greater viscosity (El-Baz et al. 2017; Gad and Abu Hashish 2018; Suresh et al. 2012). Increasing the proportion of methyl ester mixtures increases the specific fuel consumption (BSFC). For B10 and B20 combinations, the precise fuel needs are comparable to those of conventional fuel (Ibrahim S.M.A. et al. 2020; Ramesh 2016; Rao et al. 2007). Diesel-biodiesel mixtures require more fuel to run diesel engines to make them deliver the same load than pure diesel fuel does (Raghu and Ramadoss 2011; Satyanarayana and Muraleedharan 2012; Senthil Kumar et al. 2003). The BSFC of methyl ester is higher than that of diesel fuel. Diesel fuel has the lowest exhaust gas temperatures (EGT) but increases as the methyl ester content in the blend increases (Chhabra et al. 2016; Dinesha and Mohanan 2012; Mustaffa et al. 2014; Singh 2013).

Diesel oil and methyl ester combinations exhibit higher EGT because of the decreased BTE and increased BSFC. The reduced thermal efficiency of biodiesel mixtures causes heat loss increase (Ibrahim S.M.A. et al. 2024; Sorate et al. 2011). Fossil diesel has a greater air -fuel ratio than methyl ester (Ramesh et al. 2008). A richer air-fuel combination is required at greater output power, as evidenced by the fact that all studied biodiesel mixtures exhibit a decline in the air-fuel ratio (Elango and Senthilkumar 2011; Pushparaj et al. 2015; Qenawy et al. 2024). Compared to crude diesel, methyl ester mixtures have lower volumetric efficiency because of the higher EGT which heats the entering air (Pushparaj et al. 2015). The vaporization of pure diesel improves the volumetric efficiency, lowers exhaust gas temperature, and increases air density (Chalatlon et al. 2011; Vajja and Murali 2016). Diesel engines emit more CO than engines burning biodiesel blends. The amount of CO in the mixture decreases as the biodiesel ratio increases. A decline in carbon monoxide concentrations is brought on by the biodiesel's greater oxygen content, which enhances the combustion (Çetin and Yüksel 2007; Forson et al. 2004; Khalid et al. 2013). Biodiesel demonstrates higher nitrogen oxide (NO_x) emissions than crude diesel for all of the examined engine loads. Higher NO_x concentrations result from using methyl ester mixes instead of diesel fuel at higher cylinder temperatures. NO_x emission for biodiesel blends showed an increased trend in terms of engine output power. The additional oxygen in biodiesel promotes NO_x production (Mohod et al. 2014; Rao et al. 2007; Suresh et al. 2012).

Hydrocarbons (HC) emission for methyl ester mixtures had a similar pattern as crude diesel, despite the values being comparatively lower. The higher oxygen concentration in biodiesel improves combustion and lowers hydrocarbon emissions. The higher cetane number of biodiesel results in lower HC emissions (Rao et al. 2007; Suresh et al. 2012). The molecular structure of methyl ester and its mixtures, which include extra oxygen, effectively reduces the amounts of HC and CO (Agarwal and Dhar 2011; Karabektas et al. 2008). Biodiesel blends produced fewer greenhouse gas emissions than hydrocarbon diesel fuel at maximum engine loads. Biodiesel has lower carbon content than diesel oil, which results in fewer CO_2 emissions. The complete combustion is encouraged by the oxygen concentration, which also lowers carbon dioxide emissions (Chhabra et al. 2016; Ramesh 2016; Rao et al. 2007). Because they contain more oxygen than diesel oil, which helps to achieve full combustion, blends created from biodiesel and diesel oils produced decreased smoke opacity than pure diesel oil. Smoke is lower than diesel oil as the methyl ester content increases in the blend (Li et al. 2009).

According to previous research (Mulkan et al. 2024), the brake thermal efficiency (BTE) rises by 16.67% and brake-specific fuel consumption (BSFC) falls by an average of 16.67–22.69% as the engine speed increases. Compared to pure diesel, significant decreases in CO emissions (from 6.11 to 48.63%) were noted at all engine speeds. As engine speeds increased, so did hydrocarbon emissions. Engine efficiency is enhanced and exhaust emissions are decreased when pure diesel is mixed with WCO biodiesel. The emission concentration trended downwards as the blending ratio increased for the low load situation (25%). Specifically, there was an increase in NO_x emissions. A common-rail diesel engine's combustion and emissions characteristics are enhanced when waste cooking oil is used as biodiesel, both at 50 and 70% load (Meng et al. 2023).

In this investigation, methyl ester manufactured from WCO is burned in a diesel car without any hardware changes. The application of methyl ester in diesel cars is of fewer research studies. The disposal of waste cooking oil has a high cost and causes environmental and pollution problems. This study shows that biodiesel made from leftover cooking oil is a clean alternative fuel. This study only looked at low ratio biodiesel blends. Further research is necessary to determine if a high biodiesel blending ratio is appropriate for diesel vehicles, taking engine modifications into account. To assess the vehicle's performance and emissions, experiments were performed at various loads (0–30 kW) and speeds (0–33 km/h). The results recommended a biodiesel blend of 20% volume percentage as fuel in vehicles. The vehicle tests simulated both road and load conditions. The vehicle was modified to suit the present tests and was equipped with all measuring instruments and a data acquisition system. Tests were performed to measure the vehicle's performance and emissions at different loads in the laboratory, and at variable speeds on the road. For the laboratory tests, the vehicle was mounted over a chassis dynamometer simulating real operating conditions. The road cycle was designed to replicate real-world driving circumstances, including idling, acceleration, and high-speed driving. Waste cooking oil was transesterified to produce biodiesel. The physical and chemical characteristics of biodiesel mixture of 20% methyl ester are near to diesel oil, so it was selected as a substitute fuel. The impact of biodiesel mixtures on fuel consumption, EGT, and travel distance was examined. The levels of CO, NO_x, HC, and oxygen were assessed and compared to diesel fuel.

Diesel cars rely on the fuel's lubrication to keep its moving components from wearing out. Driving a car that runs on biodiesel cuts down on greenhouse gas emissions and climate change. The manufacture of biodiesel from renewable organic material can help to minimize some of the negative aspects of fossil fuel production. Using biodiesel can reduce the amount of smoke, hydrocarbons (HC), and carbon monoxide (CO) released by diesel engines. Biodiesel meets life cycle sustainability requirements and slows down the depletion of fossil fuels.

1. Materials and methods

1.1. Biodiesel production processes

Waste cooking oil was obtained from Egyptian potato-chip production factories. Before making biodiesel, the oil was purified of contaminants. The bulk moisture was then removed by preheating the oil to 100°C. The oil was then quickly stirred at 70°C during the transesterification process in a biodiesel reactor (Ibrahim S.M.A. et al. 2023) to remove the remaining moisture. The triglyceride component of the WCO interacts with the NaOH, which is dissolved in methanol at a 6:1 molar ratio. Methanol, which has a density of 0.791 g/cm^3, serves as the catalyst. After transesterification, the mixture is left for 24 hours to gravity-settle. The end results are glycerin and methyl ester and glycerin. The raw fatty acid biodiesel was water washed to eliminate any unreacted methoxide after the glycerol layer had been removed. Clean biodiesel was created when the water traces were heated out. The chemical and physical properties of WCO methyl ester and diesel oil are listed in Table 1. The calorific value of WCO methyl ester is 41,500 kJ/kg, which is lower than that of fossil diesel. How much heat is needed to create engine power depends on the heating value of the fuel. The measured cetane number for WCO biodiesel is 51. The cetane number is connected to the volatility, combustion and ignition of the fuel. Higher cetane numbers decrease the ignition delay. The flash point of WCO biodiesel is 160°C. The flash point is crucial for the secure handling and storage of diesel. Biodiesel is safer to store and handle as it has a higher flash point than crude diesel. WCO biodiesel has a density of 845 kg/m^3, compared to pure diesel's 829 kg/m^3. Compared to diesel, biodiesel has a greater viscosity. Diesel has 1.2 Cp kinematic viscosity at the same temperature as WCO biodiesel.

Table 1. Physical and chemical characteristics of WCO methyl ester and diesel

Tabela 1. Właściwości fizyczne i chemiczne estrów metylowych WCO i oleju napędowego

Properties	Test standard	Diesel oil	WCO biodiesel
Density, at 15.56°C	ASTM D-4052	829	845
Flash point [°C]	ASTM D-93	75	160
Lower heating value [kJ/kg]	ASTM D-224	42,000	41,500
Cetane number	ASTM D-13	45	51
Kinematic viscosity at 40°C [Cp]	ASTM D-445	1.2	1.8

1.2. Vehicle test rig

The tested vehicle is a four-cylinder diesel engine of 1975 cm^3, and 61 kW power (Mitsubishi L200, double cabin, model 2000). Tests were executed for both variable speeds and loads. Table 2 gives the technical parameters of the vehicle. Common-rail direct injection is used in the car. Several modifications were made in the vehicle in order to facilitate the required measurements and to accommodate the measuring instruments. The exhaust pipe was modified to be opposite the car door window so that emissions could be measured by a gas analyzer during road tests. This modification was done by making a hole in the trunk of the car and changing the path of the exhaust pipe to the top vertically with proper aerodynamics so as not to resist the flow or cause exhaust reflux. A fuel volumetric unit to measure the fuel consumption was adapted to the vehicle. The measured tank of known size was fixed at the back in the trunk of the car and connected to the fuel pump and a conversion unit was used to convert between the main fuel tank and the biodiesel tank. In order to make it easier to assess fuel consumption and the air-to-fuel ratio, this tank calculated the quantity of fuel used over time. The intake airflow was passed through an orifice on the side of the air box, which helped to lessen the pulsations of the airflow entering the engine. A U-tube manometer was used to monitor the pressure drop across the orifice. A type (K) thermocouple was placed in the air box to measure the temperatures of the intake air. Figure 1 (a) is a view of the present vehicle showing such modifications. All necessary measuring devices and data recording system were fixed in the engine as depicted in Figure 1 (b). During the field driving tests, the fuel consumption and exhaust gas temperature were assessed while burning the B20 biodiesel and diesel oil combination. Both B20 WCO biodiesel and diesel engine emissions were measured, including the CO, HC, NO_x and oxygen concentrations. Generally, the main purpose of this research is to measure the vehicle's performance and emissions at variable speeds and loads.

Table 2. Test vehicle technical specifications

Tabela 2. Dane techniczne pojazdu testowego

Parameters	Specifications
Number of cylinders	4
Displacement [cm^3]	1,975
Bore [mm]	86
Stroke [mm]	85
Maximum power [kW]	61 at 4,000 rpm
Compression ratio	23:1
Fuel injection system	IDI
Maximum torque [N. m]	174 at 2,000 rpm

(a) Back view of the tested vehicle showing exhaust and fuel systems

(b) Front view of the modified vehicle showing measuring devices

Fig. 1. Modified vehicle testing system
1 – temperature thermocouple, 2 – air speed sensor, 3 – exhaust manifold sensor, 4 – air intake tank, 5 – fuel control unit, 6 – measured fuel tank, 7 – exhaust pipe for gas analyzer probe

Rys. 1. Zmodyfikowany system testowania pojazdów

1.2.1. Variable load tests

Due to the difficulty of testing the performance with different loads while the car is running on the road, the variable load tests were conducted in the laboratory utilizing a specially designed rig. Measurements of the vehicle performance and emissions were made while it was mounted on a chassis dynamometer that was specifically designed and manufactured to simulate real--world operating circumstances. The chassis dynamometer, sometimes referred to as a rolling road, is a mechanical device that employs one or more fixed roller assemblies to replicate varied road conditions in a controlled setting. It is applied in several automobile testing and development projects. The present rig consists of two rollers per wheel and the vehicle is placed between these rollers. A dynamometer maintains the chosen speed regardless of force or other factors. For speed control and keeping a constant velocity in case the vehicle tries to accelerate while operating in this mode, the dynamometer applies an opposite force to keep the speed constant.

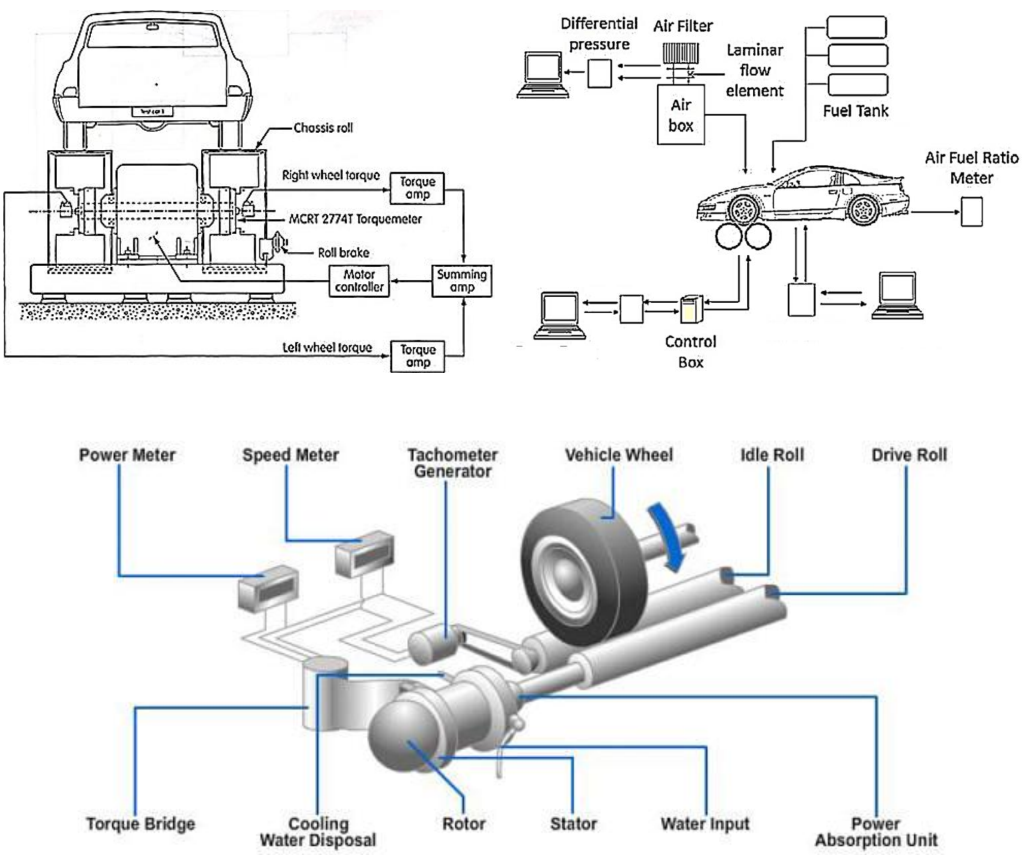

Fig. 2. Schematic diagram of the chassis dynamometer

Rys. 2. Schemat ideowy hamowni podwoziowej

The measurement of static power needs this operation mode. The maximum capacity of the car is 61 kW Therefore, when testing, approximately 50% of the capacity of the car was chosen to avoid damaging the engine. The applied loads were divided into four loads starting from zero to 30 kW. A diagram of the present chassis dynamometer system is indicated in Figure 2.

1.2.2. Road tests

Road tests on a real vehicle reflect appropriate real life results. Tests on a moving car represent real life outcomes. A moving car faces working conditions that are not encountered in test engines, thus the results are closer to reality. The road cycle, which includes idling, acceleration, and high-speed driving, may be replicated using a simulation program. The test cycle includes running at idling, low, middle, and high speeds. Low average speed, frequent acceleration and deceleration, and a low constant speed ratio are all features of the operation condition that ends the cycle. Variable speeds were chosen for the car without intervention from the driver, as the free speed was chosen for each gear from first to fourth, and it was from 0 to 33 km/h, Thus, the fuel flow rate is kept constant at the steady state idle value for all tested speeds.

2. Results and discussions

2.1. Fuel consumption

The impact of biodiesel and diesel oils on fuel consumption at various vehicle speeds (VS) and different loads (VL) is shown in Figure 3. The fuel usage increased somewhat as a result of using blends containing 20% biodiesel at a variable load but decreased at variable speed. This was brought on by the reduced heating value and energy content of methyl ester blended with diesel. Correction factors must be used to make up for the fact that the test fuels' molecules do not have the same hydrogen-to-carbon ratio as diesel. The consumption of fuel for the mixtures made from saturated methyl ester was somewhat greater than that of the blends made from unsaturated biodiesel. Higher biodiesel viscosity and density causes problems with vaporization and atomization. At a speed of 33 km/h, biodiesel can increase fuel consumption by a maximum of 17% over diesel oil. When the vehicle is loaded to 30 kW, biodiesel might increase the fuel consumption by up to 3% over diesel. The results agreed with references (Mohod et al. 2014; Rao et al. 2007).

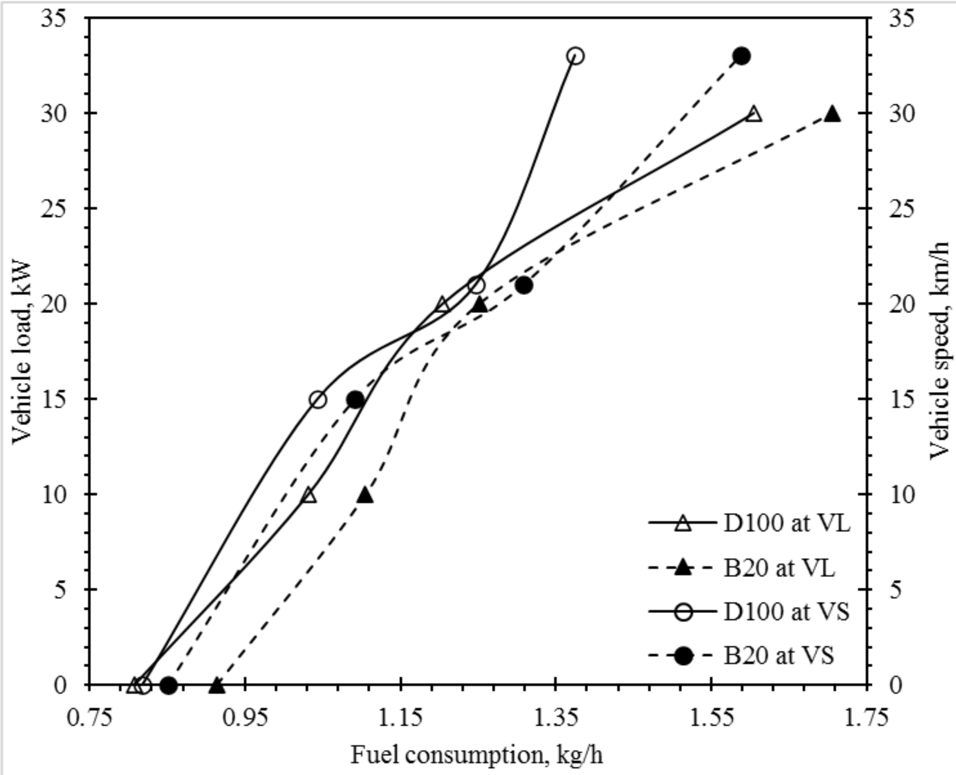

Fig. 3. Fuel consumption of diesel and biodiesel mixtures at different vehicle speeds and loads

Rys. 3. Zużycie paliwa oleju napędowego i mieszanek biodiesla przy różnych prędkościach i obciążeniach pojazdów

2.2. Exhaust gas temperature

Figure 4 depicts how the biodiesel blend affects the temperature of the exhaust gases. Applications of 20% methyl ester mixtures resulted in the largest fuel increases. The temperature of the exhaust gases decreased at variable loads but increased at variable speeds. This was a result of the biodiesel's less energy content as mixed with diesel. Because of the increased fuel use and a decrease in the calorific value, the thermal efficiency and exhaust heat loss increase. Fuel use and specific fuel consumption rise due to the reduced calorific value of the biodiesel mixture as compared to crude diesel. Problems with atomization, vaporization, improper fuel-air mixing, and lower thermal efficiency result from increased biodiesel density and viscosity. All these elements contribute to increasing BSFC and reduced BTE of biodiesel compared to diesel oil. At a speed of 33 km/h, the exhaust temperature can rise by a maximum of 6% over diesel oil. When a vehicle is loaded to 30 kW, biodiesel B20 exhaust gas temperature increases by a maximum of 2% more than diesel oil. The results are confirmed in the literature (Suresh et al. 2012).

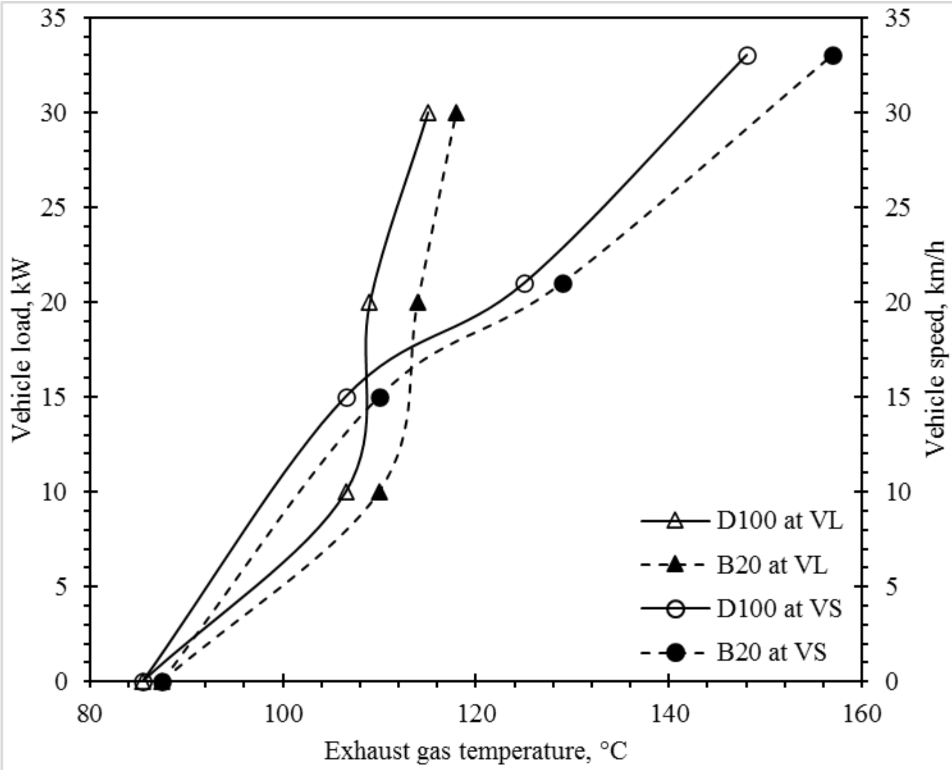

Fig. 4. Exhaust gas temperature of biodiesel blend and diesel at different vehicle speeds and loads

Rys. 4. Temperatura gazów spalinowych mieszanki biodiesla i oleju napędowego przy różnych prędkościach i obciążeniach pojazdu

2.3. Travelling distance

The effect of burning diesel and biodiesel on the distance travelled is presented in Figure 5. The increase in load led to a decrease in travelling distances because of the increase in fuel consumption. However, increasing the speed led to increased travelling distance due to the decrease in fuel consumption until the return point at about 11 km/kg, then the fuel consumption returns to an increase. The greatest increases in fuel consumption were the result of the adoption of the B20. The decreased energy content of methyl ester and its mixtures with pure diesel results in a decrease in the output power. The distance travelled is shortened owing to the decreased calorific value, higher viscosity and fuel consumption increase. The highest drop in the distance travelled when run on by biodiesel is 22% at 33 km/h vehicle speed more than for D100 fuel. When the vehicle is loaded to 30 kW, biodiesel can increase the travel distance by up to 13% in comparison with diesel fuel.

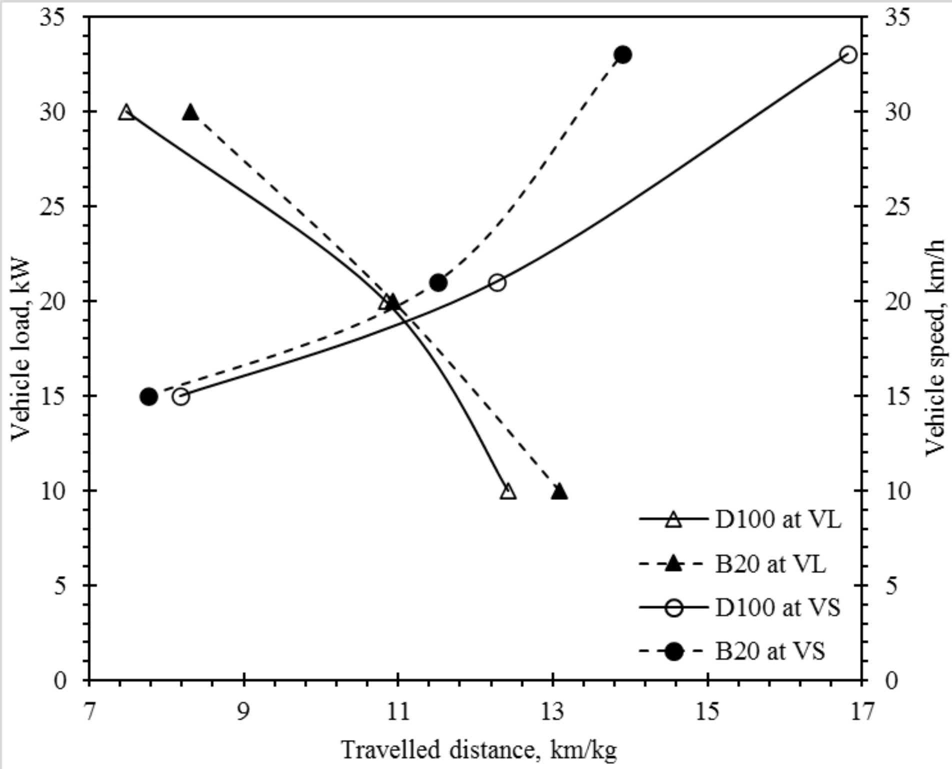

Fig. 5. Distance travelled of tested fuels at different vehicle speeds and loads

Rys. 5. Dystans przebyty na badanych paliwach przy różnych prędkościach i obciążeniach pojazdu

2.4. CO emission

Carbon monoxide concentrations of fuels at various vehicle speeds are indicated in Figure 6. The rate of CO emissions grew as the speed of the vehicle did. The burning of the B20 fuel reduces CO emissions more than diesel oil. At a speed of 33 km/h, B20 has an average 8% reduction in CO emissions less than diesel fuel because biodiesel has extra molecular oxygen, which enhances fuel burning. In addition, biodiesel's high cetane number prevented the creation of fuel-rich zones. The time available for burning was reduced as the vehicle speed climbed and fuel injection went up, as a result, the combustion process degraded, and the CO output was increased. Biodiesel with a higher cetane number and oxygen percentage burned more efficiently and released less carbon monoxide emissions. At a speed of 33 km/h, biodiesel burning reduces carbon dioxide emissions related to diesel oil by a maximum of 9%. The increase in load on the vehicle led to an increase in CO emissions due to the fuel consumption increase. The amount of time available for combustion is reduced as the weight of the vehicle grows, yet as the fuel injection increases, the combustion quality deteriorates and CO emis-

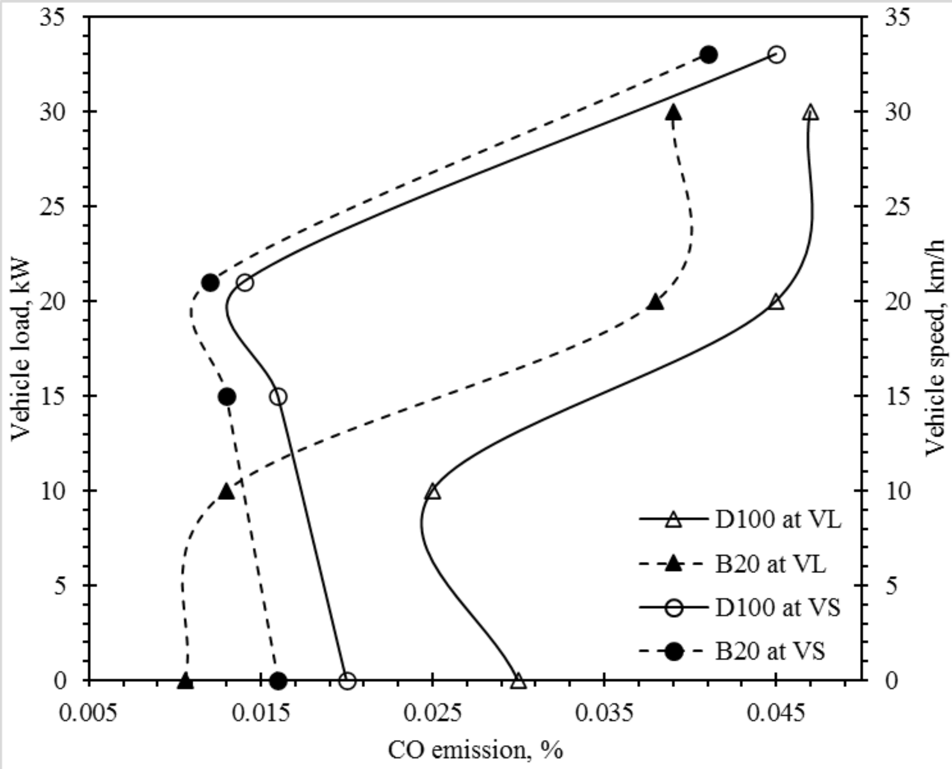

Fig. 6. CO emission at different vehicle speeds and loads for diesel and biodiesel blend

Rys. 6. Emisja CO przy różnych prędkościach pojazdów i obciążeniach dla oleju napędowego i mieszanki biodiesla

sions rise. At a vehicle load of 30 kW, the use of B20 decreased the average CO concentration over the whole test load range by 17%, approximately equating it to diesel oil. The findings were confirmed with references (Chhabra et al. 2016; Rao et al. 2007; Telgane et al. 2021) the performance and emission characteristics of four stroke single cylinder water-cooled DI diesel engine using dual hybrid biodiesel is evaluated. Dual hybrid biodiesel produced from Simarouba Oil Methyl Ester (SuOME).

2.5. CO_2 emission

The relationship between CO_2 emissions from biodiesel and engine output power is seen in Figure 7 at various vehicle speeds. Incomplete combustion is a byproduct of the diesel-biodiesel combination due to inadequate air. Because methyl ester contains more carbon than pure diesel, better combustion occurs as a result of lower CO concentrations. It has

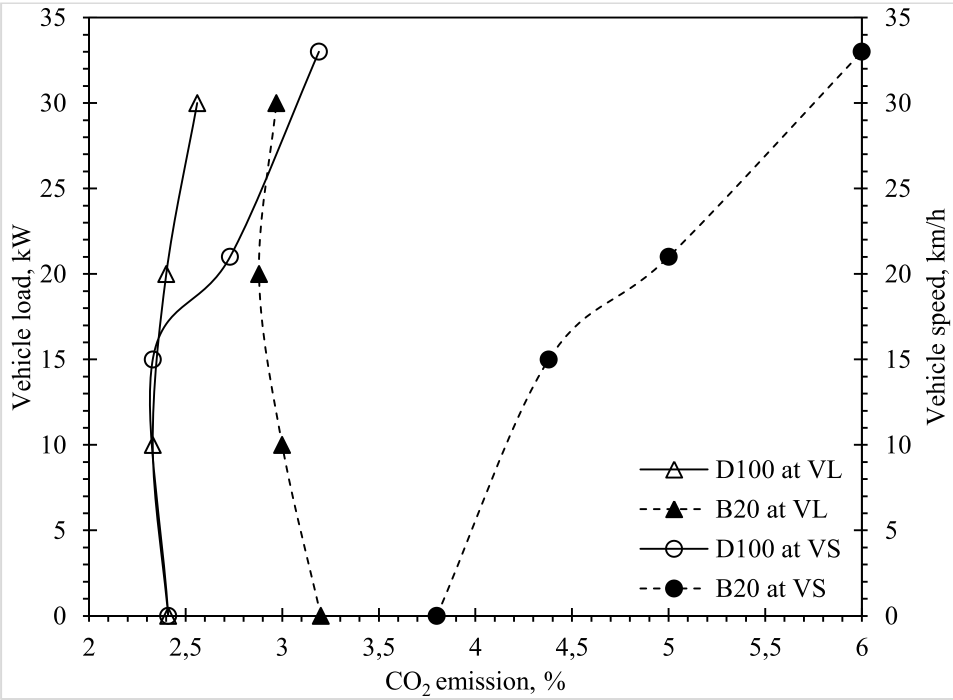

Fig. 7. CO_2 emission at different vehicle speeds for diesel and biodiesel blend

Rys. 7. Emisja CO2 przy różnych prędkościach pojazdu dla oleju napędowego i mieszanki biodiesla

been proven that biodiesel mixtures with higher CO_2 emissions have more efficient combustion. Because biodiesel contains more oxygen, complete combustion results in higher CO_2 emissions. At a speed of 33 km/h, biodiesel increases carbon dioxide emissions by 84% more than diesel oil. Because of the increasing fuel consumption, carbon dioxide percentages increase as engine brake power increases. All fuels emit more CO_2 than raw diesel due to the greater carbon content at the same load for the same fuel volume. The higher oxygen content in biodiesel reduces the emission of CO. Because biodiesel burns more efficiently than hydrocarbon diesel, it emits more CO_2 than diesel oil. For B20 diesel oil at a 30 kW vehicle load, the increase is 24%.

2.6. HC emission

The HC emission rates of biodiesel blends at various vehicle speeds are displayed in Figure 8. With speed increase, HC emission rates rose. The biodiesel blend shows decreased HC emission rates. A higher vehicle speed enhanced the biodiesel blend's ability to reduce HC emissions. Me-

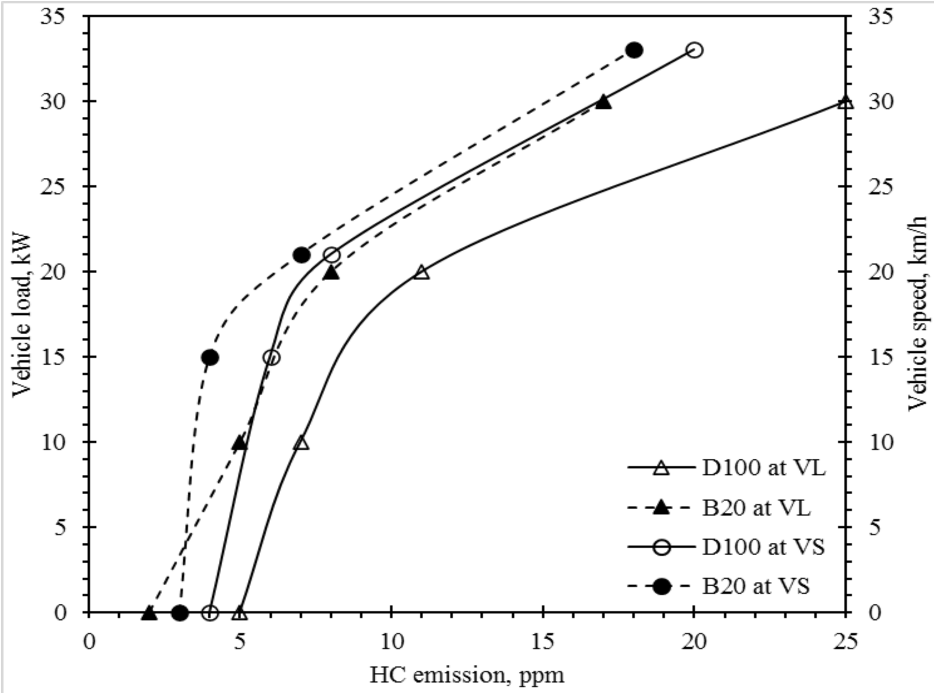

Fig. 8. HC concentrations of diesel and methyl ester blends at different vehicle speeds and loads

Rys. 8. Stężenia HC w mieszankach oleju napędowego i estrów metylowych przy różnych prędkościach i obciążeniach pojazdu

thyl ester with a higher cetane number and lower ignition delay reduced the HC concentration. Biodiesel's oxygen component promotes the full combustion of unburned HC. Due to the low volatility of biodiesel, certain HC molecules with higher molecular sizes may be absorbed in the exhaust pipe and cylinder walls, resulting in reduced HC emission. Lower HC emissions from diesel oil are produced as a result of improved fuel combustion made possible by the increased cetane number and oxygen content of biodiesel. For B20 diesel oil at a 33 km/h vehicle speed, the decrease is 10%. The biodiesel blend exhibited decreased HC emission rates. Additionally, heavier vehicle loads enhanced the ability of biodiesel to reduce HC emissions. The shortened ignition delay lowers HC emissions. Unburned HC is completely burnt, thanks to the high oxygen concentration of biodiesel. Lower HC emissions are produced as a result of improved fuel combustion caused by the greater cetane number and oxygen content of biodiesel. At 30 kW vehicle load, the use of B20 fuel reduced HC emissions by 32% than diesel oil. The present results agree with the literature (Rao et al. 2007; Telgane et al. 2021).

2.7. NO_x emission

Nitrogen oxide concentrations versus vehicle speed variation are presented in detail in Figure 9. Vehicle speed has a definite impact on NO_x emission values, and the pattern indicates that increasing speeds led to increased NO_x emissions. The rise in NO_x emissions was caused by the higher adiabatic flame temperature that resulted from the increased cylinder temperature. Because of the high fuel-air combination, NO_x emissions increased as the engine load increased. NO_x emission increase is 20%. Moreover, a high cetane number reduces the ignition delay time, promoting fuel burning and raising the temperature within the cylinder. The biodiesel oxygen content leads to improved combustion and raises the temperature at which the fuel burns in the engine cylinder. As a result, higher cylinder temperatures and richer oxygen content in the engine cylinder increase nitrogen oxide levels. For a vehicle speed of 33 km/h, B20's NO_x emission rate was 4% higher than

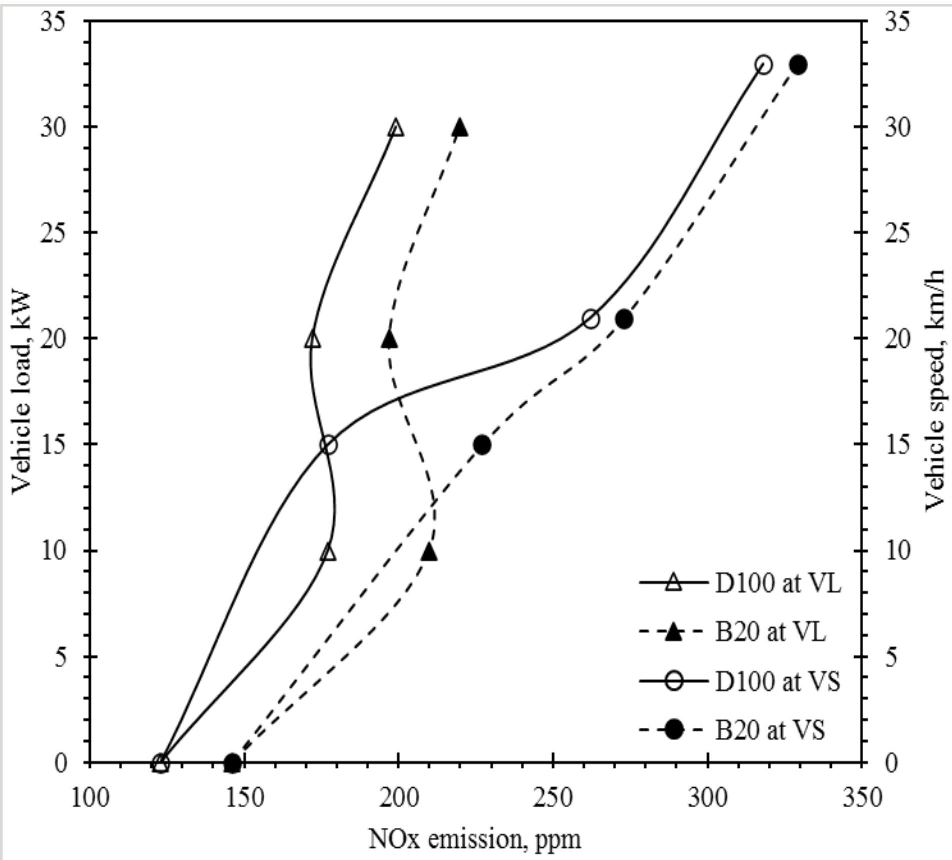

Fig. 9. NO_x emissions of diesel and methyl ester-diesel mixtures at various vehicle speeds and loads

Rys. 9. Emisje NO_x oleju napędowego i mieszanek estrów metylowych z olejem napędowym przy różnych prędkościach i obciążeniach pojazdu

D100 over the whole speed range. Heavier loads resulted in greater NO_x emissions. By reducing the ignition delay time, a high cetane number also accelerates fuel burning and raises the combustion temperature. The more proper combustion of biodiesel fuel increases the temperature in the engine cylinder due to its extra oxygen content. At a vehicle load of 30 kW, the nitrogen oxide emission rate of B20was 11% higher than that of D100 across the whole load range. The findings were supported by the literature (Agarwal and Dhar 2011; Karabektas et al. 2008).

2.8. Oxygen concentration

The fuel oxygen content under various vehicle output powers and different vehicle speeds is demonstrated in Figure 10. With increased fuel oxygen concentration, CO and CO_2 emissions decreased, which may indicate higher combustion efficiency. With a larger proportion of oxygen

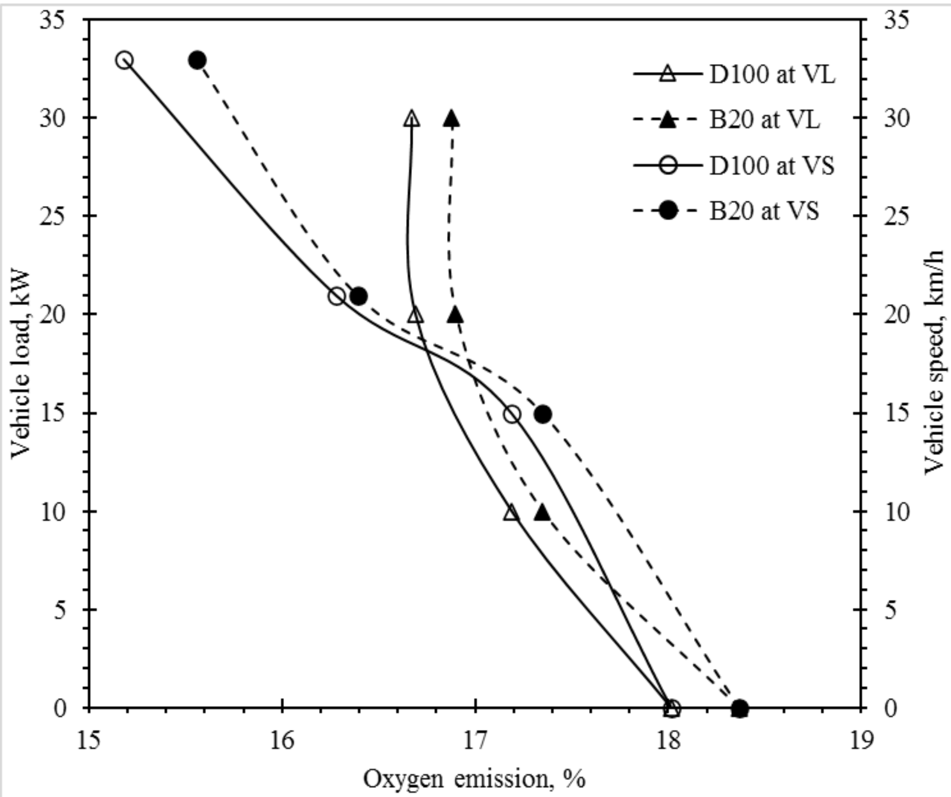

Fig. 10. Oxygen concentration of diesel and methyl ester mixtures at different vehicle loads and speeds

Rys. 10. Stężenie tlenu w mieszaninach oleju napędowego i estrów metylowych przy różnych obciążeniach i prędkościach pojazdów in the fuel, the oxygen decreases were greater. Effective reduction of CO_2 and CO emissions in biodiesel and its mixtures is due to the extra oxygen content in their molecules. Oxygen concentration affects the combustion process of biodiesel fuel. The oxygen level in the case of B20 is the highest from low to high vehicle speeds. The excess oxygen in the engine cylinder is removed during the exhaust process. At a vehicle speed of 33 km/h, the oxygen concentration of B20 was 3% higher than that of D100 over the whole speed range. With a higher fuel oxygen concentration that can boost combustion efficiency, CO emissions decreased. At increasing the percentages of oxygen in the fuel, the O_2 decreases were greater. The surplus oxygen in the molecular structure of biodiesel fuel and its mixes efficiently lowers carbon dioxide emissions. Oxygen level for B20 is the highest from the lowest to the highest vehicle load. At a vehicle load of 30 kW, the oxygen concentration of B20 was 3% higher than that of D100.

3. Comparative results

Table 3 exhibits a summary of results for the studied parameters for variable speeds and loads as percentages from fossil pure diesel.

Table 3. Performance and emission comparisons with pure diesel

Tabela 3. Porównanie wydajności i emisji czystego oleju napędowego

Parameters	Variable speeds	Variable load
	(+) Increases, (–) Decreases	
Fuel consumption	+17%	+3%
Exhaust gas temperature	+6%	+2%
Travelling distance	–22%	+13%
CO emission	–9%	–17%
CO_2 emission	+84%	+24%
HC emission	–10%	–32%
NO_x emission	+4%	+11%
O_2 concentration	+3%	+3%

The results depict that: (1) the fuel consumption has little increase with more load; (2) the travelling distance is affected more by speed; (3) the exhaust gas temperature increases little with load; (4) CO emissions are always reduced; (5) CO_2 emissions increase are affected more by speed; (6) HC reduction is almost the same for variable speeds and loads; (7) the increase in NO_x emissions are affected more by load; (8) O_2 concentrations are similarly affected by speed and load variations.

Conclusions

The burning of methyl ester resulted from waste cooking oil in compression ignition engines is the primary topic of this research. Waste cooking biodiesel was generated by the transesterification of WCO. The amount of WCO biodiesel utilized was 20% by volume. The physical and chemical properties of B20 are near to those of diesel oil. Laboratory and on-road tests were conducted to evaluate the performance and emissions of the vehicle at different loads (0–30 kW) and speeds (0–33 km/h) while burning B20 blends fuel.

The conclusions are summarized as follows:

- The better vehicle performance is at the lowest loads possible and medium speed. This leads to a longer travelling distance with a smaller amount of fuel and fewer emissions.
- The maximum increase in exhaust gas temperature and fuel consumption of biodiesel B20 are 6 and 17% over diesel oil at a vehicle speed of 33 km/h, respectively. The distance travelled, CO and HC emissions were 22, 9 and 10% less than diesel oil, respectively, but the increases in NO_x emissions and oxygen concentration were 4 and 3% higher than D100, respectively, at 33 km/h.
- At a vehicle load of 30 kW, the top increases in distance travelled, fuel consumption, and exhaust gas temperature for B20 were 13, 3 and 2%, respectively, more than diesel oil. At a vehicle load of 30 kW, B20 reduced carbon monoxide and hydrocarbon concentrations compared to diesel oil by 5 and 32%, respectively, but the increases in NO_x and oxygen levels were 11 and 3 % higher than for D100.

The present results favor the use of WCO biodiesel B20 in diesel engines as an alternative environmentally friendly fuel and for better engine performance.

For future research, more tests should be done for more speeds and loads. Higher biodiesel blends should be investigated. The addition of nano materials to biodiesel blends is recommended for research in this field.

References

Agarwal, A.K. and Dhar, A. 2011. Experimental investigation of preheated jatropha oil fuelled direct injection compression ignition engine-Part 2: Engine durability and effect on lubricating oil. *ASTM Special Technical Publication* 1477(2), pp. 355–375.

Altun et al. 2011 – Altun, S., Yasar, F. and Oner, C. 2011. Biodiesel production from raw cottonseed oil and its characterization. *Energy Education Science and Technology Part A: Energy Science and Research* 27(2), pp. 375–382. [Online] http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Biodiesel+production+from+jatropha+oil+and+its+characterization#1 [Accessed: 2-24-02-06].

Çetin, M. and Yüksel, F. 2007. The use of hazelnut oil as a fuel in pre-chamber diesel engine. *Applied Thermal Engineering* 27(1), pp, 63–67, DOI: 10.1016/j.applthermaleng.2006.04.025.

Chalatlon et al. 2011 – Chalatlon, V., Roy, M.M., Dutta, A. and Kumar, S. 2011. Jatropha oil production and an experimental investigation of its use as an alternative fuel in a DI diesel engine. *Journal of Petroleum Technology and Alternative Fuels* 2(5), pp. 76–85.

Chhabra et al. 2016 – Chhabra, M., Sharma, A. and Dwivedi, G. 2016. Performance evaluation of diesel engine using rice bran biodiesel. *Egyptian Journal of Petroleum* 26(2), pp. 511–518, DOI: 10.1016/j.ejpe.2016.07.002.

Dinesha, P. and Mohanan, P. 2012. Experimental investigations on the performance and emission characteristics of diesel engine using preheated pongamia methyl ester as fuel. *Energy Scenarios Workshop* 5, pp. 591–600.

El-Baz et al. 2017 – El-Baz, F.K.F., Gad, M.S.S., Abdo, S.M.S. and Abu Hashish, H.M.M. 2017. Comparative study of performance and exhaust emissions of a diesel engine fueled with algal, used cooked and Jatropha oils biodiesel mixtures. *International Journal of Mechanical and Mechatronics Engineering* 17(5), pp. 90–100, DOI: 10.3390/robotics6040039.

Elango, T. and Senthilkumar, T. 2011. Combustion and emission characteristics of a diesel engine fuelled with jatropha and diesel oil blends. *Thermal Science* 15(4), pp. 1205–1214, DOI: 10.2298/TSCI100614088E.

Forson et al. 2004 – Forson, F.K., Oduro, E.K. and Hammond-Donkoh, E. 2004. Performance of jatropha oil blends in a diesel engine. *Renewable Energy* 29(7), pp. 1135–1145, DOI: 10.1016/j.renene.2003.11.002.

Gad, M.S. and Abu Hashish, H.M. 2018. Effect of Egyptian roselle biodiesel on performance and emissions of diesel engine. *Egyptian Journal of Chemistry* 61(6), pp. 1161–1169, DOI: 10.21608/ejchem.2018.4425.1392.

Galushchak et al. 2023 – Galushchak, O., Burlaka, S., Kupchuk, I., Bondarenko, V. and Gontaruk, Y. 2023. Environmental indicators of the operation of a diesel generator running on a mixture of biofuels. *Polityka Energetyczna – Energy Policy Journal* 26(4), pp. 195–208, DOI: 10.33223/EPJ/170759.

Hasanin et al. 2022 – Hasanin, M.S., Hashem, A.H., Abu Hashish, H.M. and Abdelraof, M. 2022. A novel pressed coal from citrus and cooking oil wastes using fungi. *Bioresources and Bioprocessing* 9(1), 95, DOI: 10.1186/s40643-022-00582-8.

Ibrahim M.M. et al. 2022 – Ibrahim, M.M., Elsaman, H.A., Hashish, H.M.A., El-Sayed, A.B. and Mostafa, E. 2022. Effect of the Duration Time of Cooking Frequency on Chemical and Physical Properties of Waste Cooking Oil Used for Biodiesel Production. *Egyptian Journal of Chemistry* 65(12), pp. 415–426, DOI: 10.21608/EJCHEM.2022.95410.5473.

Ibrahim S.M.A. et al. 2017 – Ibrahim, S.M.A., Abed, K.A.A., Gad, M.S.S. and Abu Hashish, H.M. 2017. Optimum oil yield from Egyptian Jatropha seeds using screw press. *International Journal of Mechanical and Mechatronics Engineering* 17(1), pp. 47–56.

Ibrahim S.M.A. et al. 2023 – Ibrahim, S.M.A., Abed, K.A., Gad, M.S. and Abu Hashish, H.M. 2023. A semi-industrial reactor for producing biodiesel from waste cooking oil. *Biofuels* 14(4), pp. 393–403, DOI: 10.1080/17597269.2022.2145758

Ibrahim S.M.A. et al. 2020 – Ibrahim, S.M.A., Abed, K.A., Gad, M.S. and Hashish, H.M.A. 2020. Experimental study on the effect of preheated Egyptian Jatropha oil and biodiesel on the performance and emissions of a diesel engine. *International Journal of Mechanical and Mechatronics Engineering* 20(1), pp. 59–69.

Ibrahim S.M.A. et al. 2024 – Ibrahim, S.M.A., Abed, K.A., Gad, M.S. and Hashish, H.M.A. 2024. Performance and emissions of a diesel engine burning blends of Jatropha and waste cooking oil biodiesel. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 238(4), pp. 1157–1169, DOI: 10.1177/09544062231181809.

Karabektas et al. 2008 – Karabektas, M., Ergen, G. and Hosoz, M. 2008. The effects of preheated cottonseed oil methyl ester on the performance and exhaust emissions of a diesel engine. *Applied Thermal Engineering* 28(17–18), pp. 2136–2143, DOI: 10.1016/j.applthermaleng.2007.12.016.

Khalaf et al. 2023 – Khalaf, M., Abdel-Fadeel, W., Hashish, H.M.A., Wapet, D.E.M., Mahmoud, M.M., Elhady, S.A. and Esmail, M.F.C. 2023. Experimental Investigation of Different Extraction Methods for Producing Biofuel from Jatropha Seeds and Castor Seeds. *International Journal of Energy Research 2023*, DOI: 10.1155/2023/1780536.

Khalid et al. 2013 – Khalid, A., Osman, S.A., Jaat, M.N.M., Mustaffa, N., Basharie, S.M. and Manshoor, B. 2013. Performance and emissions characteristics of diesel engine fuelled by biodiesel derived from palm oil. *Applied Mechanics and Materials* 315, pp. 517–522, DOI: 10.4028/www.scientific.net/AMM.315.517.

Khater et al. 2023 – Khater, E.S.G., Abd Allah, S.A., Bahnasawy, A.H. and Hashish, H.M.A. 2023. Enhancing bio-oil yield extracted from Egyptian castor seeds by using microwave and ultrasonic. *Scientific Reports* 13(1), 4606, DOI: 10.1038/s41598-023-31794-3.

Khater et al. 2024 – Khater, E.S.G., AbdAlla, S.A., Bahnasawy, A.H. and AbuHashish, H.M. 2024. Improvement of the production of bio-oil and biodiesel from Egyptian Jatropha seeds by using microwave and ultrasonic. *Scientific Reports* 14(1), 1882, DOI: 10.1038/s41598-024-51579-6.

Koh, M.Y. and Tinia, T.I. 2011. A review of biodiesel production from Jatropha curcas L. oil. *Renewable and Sustainable Energy Reviews* 15(5), pp. 2240–2251, DOI: 10.1016/j.rser.2011.02.013.

Kumar, A. and Sharma, S. 2008. An evaluation of multipurpose oil seed crop for industrial uses (Jatropha curcas L.): A review. *Industrial Crops and Products* 28(1), pp. 1–10, DOI: 10.1016/j.indcrop.2008.01.001.

Kupchuk et al. 2022 – Kupchuk, I., Burlaka, S., Galushchak, A., Yemchyk, T., Galushchak, D. and Prysiazhniuk, Y. 2022. Research of autonomous generator indicators with the dynamically changing component of a two-fuel mixture. *Polityka Energetyczna – Energy Policy Journal* 25(2), pp. 147–162, DOI: 10.33223/EPJ/150746.

Li et al. 2009 – Li, S., Wang, Y., Dong, S., Chen, Y., Cao, F. and Chai, F. 2009. Biodiesel production from Eruca Sativa Gars vegetable oil and motor, emissions properties. *Renewable Energy* 34(7), pp. 1871–1876, DOI: 10.1016/j.renene.2008.12.020.

Meng et al. 2023 – Meng, J., Xu, W., Meng, F., Wang, B., Zhao, P., Wang, Z., Ji, H. and Yang, Y. 2023. Effects of waste cooking oil biodiesel addition on combustion, regulated and unregulated emission characteristics of common-rail diesel engine. *Process Safety and Environmental Protection* 178, pp. 1094–1106, DOI: 10.1016/J.PSEP.2023.08.065.

Mohamed et al. 2022 – Mohamed, R.M., Hashish, H.M.A., Abdel-Samad, H.A., Awad, M.E. and Kadry, G.A. 2022. A Competent, Humble Cost Catalyst from Biowaste: High Performance and Combustion Characteristics of Alternative Diesel Fuel. *Egyptian Journal of Chemistry* 65(13), pp. 265–277, DOI: 10.21608/EJCHEM.2022.117718.5306.

Mohod et al. 2014 – Mohod, R.T., Bhansali, S.S., Moghe, S.M. and Kathoke, T.B. 2014. Preheating of Biodiesel for the Improvement of the Performance Characteristics of Di Engine: A Review. *International Journal of Engineering Research and General Science* 2(4), pp. 747–753. [Online] https://www.mendeley.com/catalogue/2e8667e2-e00c-389f-bc96-e1b0ebd8976d/?utm_source=desktop&utm_medium=1.19.4&utm_campaign=open_catalog&userDocumentId=%7B553e3d36-a65e-4b09-9c65-11df76bd5f5c%7D [Accessed: 2024-03-15].

Mulkan et al. 2024 – Mulkan, A., Mohd Zulkifli, N.W., Husin, H., Ahmadi and Dahlan, I. 2024. Performance and emissions assessment under full load operation of an unmodified diesel engine running on biodiesel-based waste cooking oil synthesized using JPW solid catalyst. *Renewable Energy* 224, DOI: 10.1016/J.RENENE.2024.120145.

Mustaffa et al. 2014 – Mustaffa, N., Khalid, A., Sies, M.F., Zakaria, H. and Manshoor, B. 2014. Preheated biodiesel derived from vegetable oil on performance and emissions of diesel engines: A review. *Applied Mechanics and Materials* 465–466, pp. 285–290, DOI: 10.4028/www.scientific.net/AMM.465-466.285.

Pushparaj et al. 2015 – Pushparaj, T., Ramabalan, S. and Selvan, V.A.M. (2015). Performance and emission characteristics of CI engine, fuelled with diesel and oxygenated fuel blends. *International Journal of Global Warming* 7(2), pp. 173–183, DOI: 10.1504/IJGW.2015.067748.

Qenawy et al. 2024 – Qenawy, M., Khalaf, M., Wang, J., Tian, J., Zuo, L., Mustafa, H.M.M. and Esmail, M.F.C. 2024. Performance and emission of extracted biodiesel from mixed Jatropha-Castor seeds. *Fuel* 357, DOI: 10.1016/j.fuel.2023.130060.

Raghu, R. and Ramadoss, G. 2011. Optimization of injection timing and injection pressure of a DI diesel engine fueled with preheated rice bran oil. *International Journal of Energy and Environment* 2(4), pp. 661–670.

Ramesh, A. 2016. Performance and Emission Characteristics of CI Engine Fuelled with Coconut Testa Biodiesel. *Journal of Environmental Research and Development* 4(1), pp. 777–782, DOI: 10.15680/IJIRSET.2016.0505629.

Ramesh et al. 2008 – Ramesh, D., Sampathrajan, A. and Nadu, T. 2008. Investigations on Performance and Emission Characteristics of Diesel Engine with Jatropha Biodiesel and Its Blends. *Journal of Renewable Energy* X(3), pp. 1–13.

Rao et al. 2007 – Rao, G.L.N., Prasad, B.D., Sampath, S. and Rajagopal, K. 2007. Combustion analysis of diesel engine fueled with Jatropha oil methy Lester-diesel blends. *International Journal of Green Energy* 4(6), 645–658, DOI: 10.1080/15435070701665446.

Satyanarayana, M. and Muraleedharan, C. 2012. Experimental studies on performance and emission characteristics of neat preheated vegetable oils in a di diesel engine. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 34(18), pp. 1710–1722, DOI: 10.1080/15567036.2010.485172.

Senthil Kumar et al. 2003 – Senthil Kumar, M., Ramesh, A. and Nagalingam, B. 2003. An experimental comparison of methods to use methanol and Jatropha oil in a compression ignition engine. *Biomass and Bioenergy* 25(3), pp. 309–318, DOI: 10.1016/S0961-9534(03)00018-7.

Shah et al. 2004 – Shah, S., Sharma, A. and Gupta, M.N. 2004. Extraction of oil from Jatropha curcas L. seed kernels by enzyme assisted three phase partitioning. *Industrial Crops and Products* 20(3), pp. 275–279, DOI: 10.1016/j.indcrop.2003.10.010.

Shah et al. 2005 – Shah, S., Sharma, A. and Gupta, M.N. 2005. Extraction of oil from Jatropha curcas L. seed kernels by combination of ultrasonication and aqueous enzymatic oil extraction. *Bioresource Technology* 96(1), pp. 121–123, DOI: 10.1016/j.biortech.2004.02.026.

Singh, B.P. 2013. Performance and emission characteristics of conventional engine running on jatropha oil. *Journal of Mechanical Science and Technology* 27(8), pp. 2569–2574, DOI: 10.1007/s12206-013-0641-6.

Sorate et al. 2011 – Sorate, K.A., Bhor, S.K., Deshmukh, P.A. and Sable, M.J. 2011. Experimental Investigation for Blended Jatropha Bio-diesel as an Alternative Fuel in Compression Ignition Engine. *International Journal of Engineering* 4(3), pp. 343–349.

Suresh et al. 2012 – Suresh, R., Raddy, S. and Yathish, K.V. 2012. Experimental Investigation of Diesel Engine Using Blends of Jatropha Methyl Ester as Alternative Fuel. *International Journal of Emerging Technology and Advanced Engineering* 2(7), pp. 419–428.

Telgane et al. 2021 – Telgane, V., Godiganur, S., Keerthi Kumar, N. and Chandrashekar, T.K. 2021. Performance and emission characteristics of c.I engine fuelled with hybrid biodiesel. *International Journal of Vehicle Structures and Systems* 13(1), pp. 6–9, DOI: 10.4273/ijvss.13.1.02.

Vajja, S.R. and Murali, R.B.V. 2016. Performance Evaluation of Diesel Engine with Preheated Bio Diesel with Additives. *IOP Conference Series: Materials Science and Engineering* 149(1), DOI: 10.1088/1757-899X/149/1/012206.

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Osiągi opracowanego pojazdu z silnikiem Diesla przystosowanego do zasilania biodieslem WCO przy zmiennych prędkościach i obciążeniach

Streszczenie

Głównym tematem badań podjętych w niniejszym artykule są emisje i osiągi pojazdów napędzanych biodieslem odpadowym z oleju spożywczego. Biodiesel powstał w procesie transestryfikacji o właściwościach fizycznych i chemicznych porównywalnych z olejem napędowym. B20 to 20% ester metylowy zmieszany z olejem napędowym. Zmodyfikowano pojazd z silnikiem diesla i wyposażono go we wszystkie przyrządy pomiarowe potrzebne do przeprowadzenia wszystkich eksperymentów. Przeprowadzono testy zmiennej prędkości i obciążenia pojazdu, aby zmierzyć jego osiągi i emisję przy różnych obciążeniach (0–30 kW) i różnych prędkościach (0–33 km/h). Prędkość pojazdu była maksymalną osiąganą na każdym biegu przy stałym natężeniu przepływu paliwa bez zewnętrznego sterowania paliwem w stanie ustalonym. Przy prędkości pojazdu wynoszącej 33 km/h największe wzrosty zużycia paliwa i temperatury spalin dla biodiesla B20 wyniosły odpowiednio 17 i 6% w porównaniu do czystego oleju napędowego. Przy prędkości pojazdu wynoszącej 33 km/h B20 zmniejszył przebyty dystans oraz stężenie tlenku węgla i węglowodorów w porównaniu do oleju napędowego odpowiednio o 22, 9 i 10%. Przy prędkości pojazdu wynoszącej 33 km/h przyrosty stężeń tlenków azotu i tlenu B20 były w całym badanym zakresie obciążeń odpowiednio o 4 i 3% większe niż w przypadku surowego oleju napędowego. Największy wzrost zasięgu, zużycia paliwa i temperatury spalin dla B20 w porównaniu z olejem napędowym wyniósł odpowiednio 13, 3 i 2% przy obciążeniu pojazdu 30 kW. Mieszanka B20 zmniejszyła emisję CO i węglowodorów związaną z olejem napędowym odpowiednio o 17 i 32% przy obciążeniu pojazdu 30 kW. Wzrosty stężeń tlenków azotu i tlenu B20 w całym zakresie obciążenia były odpowiednio o 11 i 3% wyższe niż w przypadku czystego oleju napędowego przy obciążeniu pojazdu 30 kW. Mieszankę biodiesla B20 zaleca się stosować w pojazdach pod warunkiem, że pojazd jest umiarkowanie obciążony.

Słowa kluczowe: WCO, biodiesel, pojazd, obciążenie zmienne, zmienna prędkość