

# Emissions and performance of a single cylinder diesel engine using walnut-diesel blends

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**Abstract.** This paper investigates performance and emission characteristics of a single cylinder diesel engine which is fuelled with different blends of walnut oil biodiesel and diesel. Crude walnut oil was converted into walnut oil methyl ester by alkaline-catalyzed transesterification process. Various proportions of walnut oil biodiesel and Diesel are prepared on volume basis, and physically-chemically characterized. Engine performance (brake specific fuel consumption, brake thermal efficiency, and exhaust gas temperature) and emissions (HC, CO, CO<sub>2</sub> and NO<sub>x</sub>) were measured at five engine loads. The results obtained showed an increase in BSFC and EGT and a decrease in BTE for all biodiesel blends. The emissions showed that biodiesel leads to a reduction of CO by 61.53% and HC by 30.3% and an increase of CO<sub>2</sub> by 5.11% and NO<sub>x</sub> by 14.68%. Therefore it is concluded from the present experimental study that biodiesel of walnut can be used as alternative fuel for diesel engines.

## 1. Introduction

Due to depletion of fossil fuels and resulting global warming and air pollution biofuels are getting worldwide consideration. The transportation system consumes increased quantity of non-renewable petroleum fuels. Scientists and researchers all over the world found that biodiesel can be used for partial replacement of mineral diesel in terms of engine performance, emissions and combustion characteristics [1-4]. There are different kinds of alternative fuels obtained from vegetable oils, animal fats and waste oil [5]. Several studies have investigated the use of biodiesel from castor oil [6], soybean oil [7], camelina seed [8], sunflower oil [9], palm oil [10] and rapeseed oil [11] in diesel engines. Biodiesel is referred as fatty acid alkyl esters and is derived from renewable lipid sources by a process of transesterification [12]. The transesterification process is a reaction in which the triglycerides of the vegetable oil react with an alcohol in the presence of a catalyst (sodium hydroxide and potassium hydroxide) [13,14]. Several experimental investigations have been performed to evaluate the performance and emission characteristics of biodiesel-fueled engines. Combustion of biodiesel fuel produces less particulate matter (PM), hydrocarbon (HC), smoke and carbon monoxide (CO) emissions [15, 16]. In order to improve the psychical chemical properties of biodiesel many researchers had tried adding different blending components [17]. In comparison with other vegetable oils, walnut oil has the highest amounts of polyunsaturated fatty acids (up to 78% of the total content of fatty acids). The fatty acid composition of walnut oil contains linoleic acid (49 to 63%),  $\alpha$ -linoleic acid (8 to 15.5%), oleic acid (13.8 to 26.1%), palmitic acid (6.7 to 8.7%), and stearic acid (1.4 to 2.5%) [18-20]. Romania is the 10th largest producer of nuts in the world with 28.700 tons produced in 2014 on a cultivated area of 1750 hectares. Almost 25% of total EU production comes from Romania



[21]. Hu et al. [22] investigated the effects of molar ratio of methanol to oil, catalyst dosage, and temperature on reaction yield and found a biodiesel transformation rate of (97.2%). A ratio methanol to oil 8:1, reaction time 90 min, 1% catalyst generate a walnut biodiesel with properties closed to diesel fuel. Moser R.B. [23] studied the properties of blends (B2, B5, B10 and B20) from hazelnut, walnut and peanut biodiesel fuel. Blends containing biodiesel of hazelnut and walnut exhibited improved cold flow properties. With the increase in biodiesel content the oxidative stability and calorific value of blend was negatively affected, whereas lubricity was improved. Several experimental investigations have been carried out by Rasheda et al. [24] on a multi-cylinder diesel engine with moringa, palm and jatropha biodiesel with a concentration of 20% by volume. They found a reduction on brake power (6.92–8.75%), CO (22.93–32.65%) and HC (11.84–30.26%) emissions and an increase on BSFC (5.42–8.39%) and NO<sub>x</sub> (6.91–18.56%) than diesel fuel. In another set of experiments Habibullah et al. [25] conducted a comprehensive study on performance and emissions of 30% palm biodiesel blend with petrodiesel. According to their results all the biodiesel blends showed an increase of brake-specific fuel consumption (BSFC) by 8.55–9.03% and a decrease of the brake thermal efficiency by 3.84–5.03% compared to diesel fuel. Also CO and HC emissions decrease with 13.75–17.97% and 18.26–31.21%. In a previous study Khiari et al. [26] on a single cylinder, direct injection diesel engine with pistacia lentiscus biodiesel combustion parameters, performance and pollutant emissions are compared with those of diesel fuel. The BSFC for biodiesel is 17.6% and 9.7% higher than the diesel fuel and the emission of CO, HC particulate matter are reduced at full engine load with 25%, 45% and 17%. The aim of this study is to determine the fuel properties, parameters and emissions of a single cylinder engine fuelled with blends of walnut oil biodiesel. No research was conducted in the literature to investigate the performance and emissions characteristics of this type of fuel in diesel engine.

## 2. Materials and methods

### 2.1 Materials

The walnuts nuts were purchased from a local vendor in Romania. Diesel fuel was purchased from a Lukoil gas station in Craiova (type Euro L Diesel). The chemicals used for the transesterification reaction were purchased from Laborex Romania.

### 2.2 Production of WME

The walnut kernels were subjected to an extraction process using a press PU-200 to produce raw oil. After pressing, the raw oil was filtered to remove impurities. A titration was performed to determine the steps for biodiesel production. Alkaline-catalyzed transesterification was used to produce WME. A ratio of 6:1 methanol and catalyst (NaOH 1 w/w% of oil) in a reactor at constant temperature (65°C) was stirred for 2 hours. The mixture was cooled to room temperature and to settle down for 24 hours.

The mixture separated by gravity into biodiesel and glycerol. Biodiesel is separated and purified to remove catalyst and methanol (magnetic separation).

### 2.3 Samples blending

The blends of methyl esters were prepared with a laboratory homogenizer. WME (B100) was blended with diesel fuel in specified volumetric ratios at 10% (B10), 20% (B20), 30 % (B30) and 75% (B75).

The homogenizer was set at 1800 rpm to mix the samples for 30 min.

### 2.4 Properties analysis

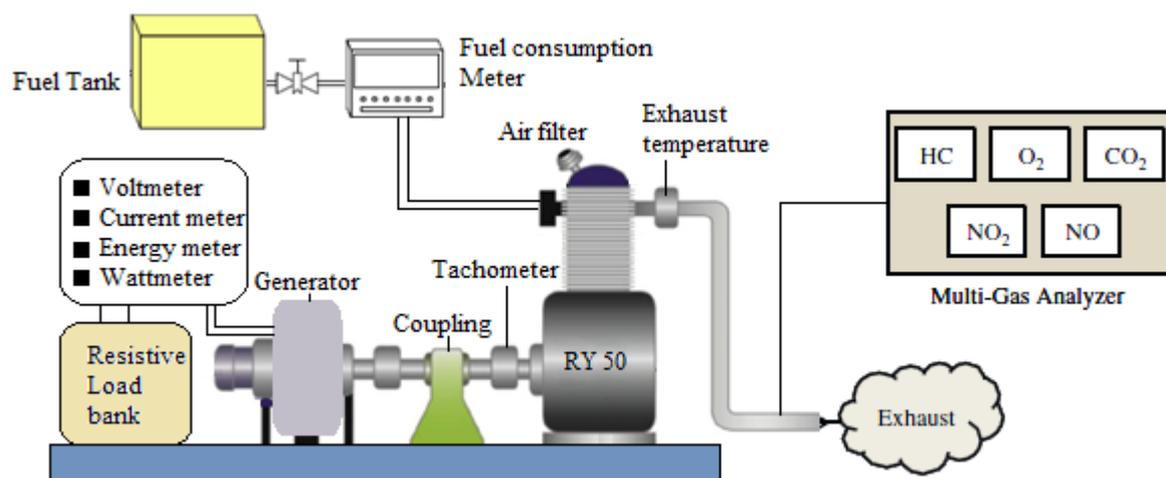
The chemical and physical properties of all samples were assessed in the Laboratory of Thermodynamics and Thermal Machines and Laboratory of Fuels, University of Craiova. The major properties including viscosity, density, flash point, calorific value, cetane number, cloud and pour point were determined using several methods. Table 1 shows the important properties of fuel along with biodiesel standards.

**Table 1.** Properties of the fuels and standards

Properties	Units	Method	Diesel	B10	B20	B30	B75	WME (B100)	Limits for biodiesel	
									EN	ASTM
Kinematic viscosity at 40 °C	mm <sup>2</sup> s <sup>-1</sup>	ASTM D445	3.078	3.18	3.31	3.43	3.77	3.88	3.5-5.0	1.9-6
Cloud Point	°C	ASTM D2500	-18	-15.3	-14.4	-10.1	-8.1	-6.1	-	-
Pour Point	°C	ASTM D97	-32	-29.1	-26.8	-24.7	-18.6	-10.0	-	-
Calorific value	MJ/kg	ASTM D4809	44	43.2	42.7	42.2	41.5	41.18	-	-
Flash point	°C	ASTM D93	68	72	78	84	98	170	101 Min.	130 Min.
Density at 15 °C	kg/m <sup>3</sup>	EN ISO 3675	816	820.1	825.8	832.2	855.7	864	860-900	860-900
Cetane number	-	ASTM D613	49	50.1	50.86	51.23	53.06	54	51 Min.	47 Min.

### 2.5 Engine test facility and experimental conditions

In this study a Ruggerini RY 50 model, single cylinder, four-stroke diesel engine, typically used in the agricultural sector was used for tests. The schematic diagram of experimental setup is shown in figure 1. The technical details of the engine are listed in table 2. The engine was coupled with a generator (type Ce 160s, 110V, 44A) and the speed of the engine was kept constant at 1500 rpm. A resistive load bank was used to load the engine at 20, 40, 60, 80 and 100% for different blends of biodiesel and diesel fuel. Fuel consumption (model DFM 250D) and exhaust temperatures (KIMO MP 200 thermocouple type K, temperature range -200...1300 °C) were also measured. Exhaust gas emissions were measured with a gas analyzer type Stargas 898 (table 3). This analyzer measures CO, CO<sub>2</sub>, HC, O<sub>2</sub> and NO in the exhaust gas. The ambient conditions were monitored by a barometer and a thermometer. The engine is first started with diesel fuel until a steady operating condition was obtained (cooling water and lubricating oil and have reached 85°C). The experiments were repeated three time and the average values of emission and performance were taken for measurements.

**Figure 1.** Schematic diagram of experimental apparatus.

**Table 2.** Engine specifications [27]

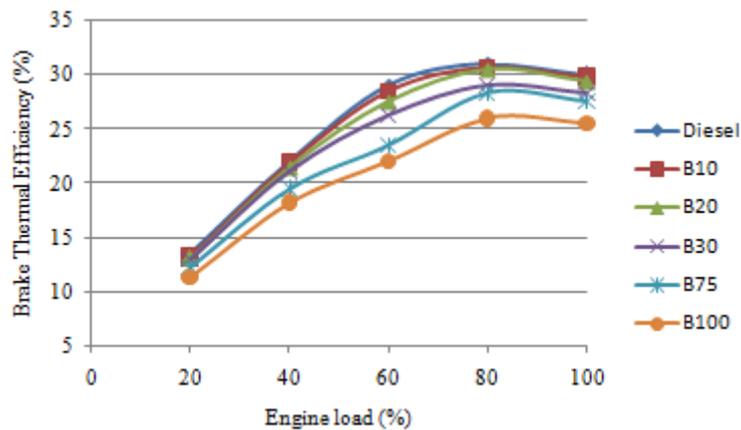
Manufacturer	Ruggerini
Model	RY 50
Configuration	Single cylinder vertical
Type	Direct injection diesel
Displacement	224 cc
Bore	69 mm
Stroke	60 mm
Compression ratio	21:1
Power	3.5 kW
Speed	3600 rpm
Type of cooling	Air cooling
Max. torque	10.4 Nm at 2400 rpm
Weight	28 kg

**Table 3.** Details of the exhaust gas analyzer [28]

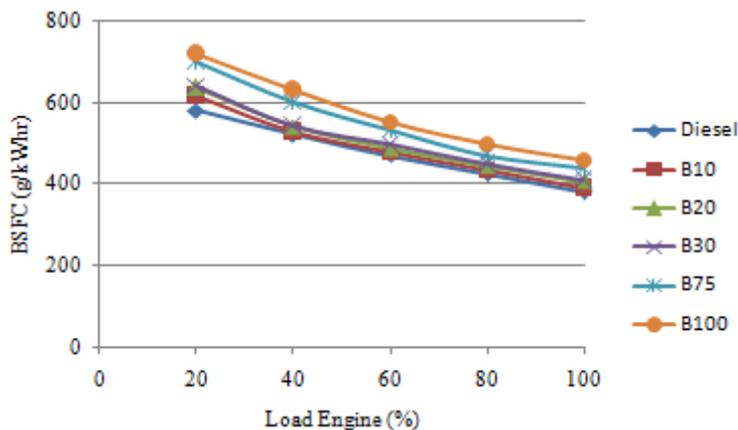
Equipment name	Method	Measurement	Range	Resolution	Accuracy	
STARGAS 898	Non-dispersive Infrared Spectroscopy	CO	0-15 Vol%	0.00	0..10%	±0.002% abs./ ±3% rel.
			10.01..15%	1	10.01..15%	±5% rel.
	Non-dispersive Infrared Spectroscopy	CO <sub>2</sub>	0-20 Vol%	0.01	0.00..16.00 %	±0.03% abs./ ±3% rel.
			16.01..20.00%		16.01..20.00%	±5% rel.
	Non-dispersive Infrared Spectroscopy	HC	0-30000 ppm	1	0..2000 ppm	±4ppm abs./ ±3% rel.
					2001..15000 ppm	±5% rel.
					15001..30000 ppm	±8% rel.
	Electrochemical detection	O <sub>2</sub>	0-25 Vol%	0.01	0.00..25%	±0.1% abs./ ±3% rel.
	Electrochemical detection	NO	0-5000 ppm	1	0..4000 ppm	±25ppm abs./ ±5% rel.
					4001..5000 ppm	±5% rel.

### 3. Results and discussion

Figure 2 shows the variation of brake thermal efficiency for the blends of walnut biodiesel. From the chart it is seen that BTE increases with the load of the engine up to 80% and decreases at maximum load due to the incomplete combustion. The decrease in BTE found in biodiesel blends can be attributed to the higher values of density and viscosity which influences atomization and vaporization of the fuel. The BTE obtained at full load for diesel, B10, B20, B30, B75 and B100 are 30.02%, 29.81%, 29.24%, 28.30%, 27.11% and 25.53% respectively. These results have been reported in the literature by different researchers [29,30]. Banapurmath et al. [31] studied biodiesel from marotti and honge oil in a single cylinder diesel engine. They found a decrease in BTE with higher blends. At 80% load BTE of marotti biodiesel was 28.38% while in the case of diesel fuel 31.25%. At the same load BTE of honge biodiesel was 29.51%. Rao et al. [32] found a decrease in BTE of jatropha biodiesel in a single cylinder direct injection diesel engine. The decrease in BTE of jatropha blends was due to the early start of combustion of biofuel with an increase in compression work and heat loss. Figure 3 shows the variation of brake specific fuel consumption for diesel and blends of walnut biodiesel. It was observed that BSFC values are higher for biodiesel blends at all engine loads.



**Figure 2.** Variation in brake thermal efficiency with load.

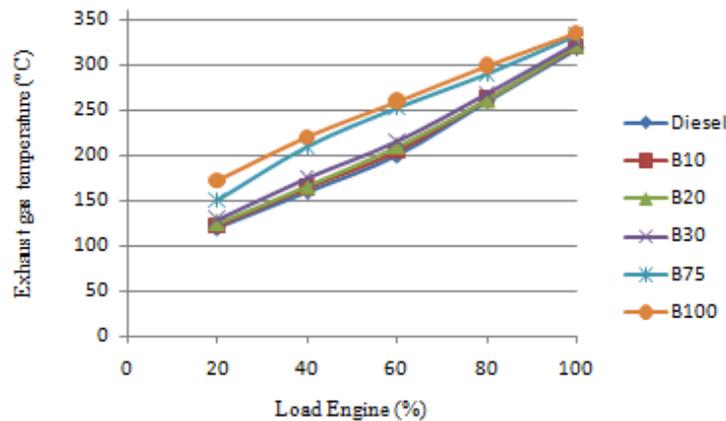


**Figure 3.** Variation in brake specific fuel consumption with load.

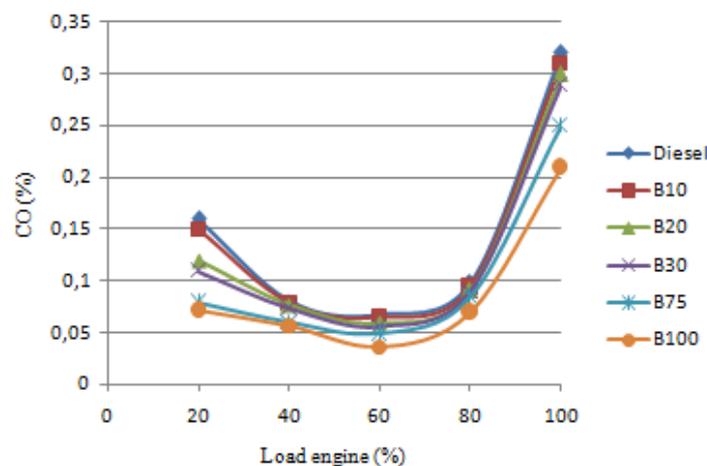
At full load BSFC values for diesel, B10, B20, B30, B75 and B100 are 380 g/kWh, 391 g/kWh, 406 g/kWh, 410 g/kWh, 436 g/kWh, and 455 g/kWh, respectively. This phenomenon occurs due to lower calorific value and higher density of biodiesel [33]. These findings are supported in the literature by various reports [34,35]. McCarthy et al. [36] found that a mixture of animal tallow (80%)-canola oil methyl ester (20%) and chicken tallow (70%)-waste cooking oil methyl ester (30%) increase BSFC with 7% and 10% compared to diesel. Also Utlu and Kocak [37] reported an increase with 14.34% of BSFC of biodiesel from waste frying oil.

Exhaust Gas Temperature (EGT) increases with the increase in load for all the blends and diesel (figure 4). The EGT is an indicator of the heat of the blends tested during combustion period [38]. From the results it can be seen that the EGT in full load for B100 (335°C) is very closer to that of diesel (318°C). Higher blends of biodiesel exhibits high temperature due to the higher oxygen content which leads to better combustion [39]. Godiganur et al. [40] tested mahua oil methyl ester and its blends with diesel and observed an increase with 12% of EGT of biodiesel. Buyukkaya [41] investigated the EGT of rapeseed biodiesel and reported a temperature of 490°C in the case of B100 whereas the corresponding value with diesel was 475°C.

CO is formed during the combustion process and depends upon carbon content, oxygen content and combustion efficiency of the fuel [42]. CO is an indicator of incomplete combustion and is produced when the carbon from the fuel is partially oxidized. Figure 5 shows the variation in CO emission with



**Figure 4.** Variation in exhaust gas temperature with load.



**Figure 5.** Variation in CO emission with load.

respect to variation in load. Compared with diesel, a decrease in CO emission is observed when walnut biodiesel and its blends are used. The average CO emission for B10, B20, B30, B75 and B100 were less than that of diesel by 2.98%, 12.5%, 19.34%, 30.5% 61.53% at 60% load of the engine. It is observed that CO emissions decrease up to 60 % load and increase after for all the tested fuels.

The decrease of CO emissions with the increase of biodiesel percent in the blend is due to the increase of oxygen content and temperature of combustion. Raheman and Phadataré [43] investigated in diesel engine different blends of karanja oil methyl ester and found a reduction in CO emissions by 74% compared with diesel fuel. A 25.8% reduction in CO emission was found by Subbaiah and Gopal [44] with rice bran oil biodiesel.

The variation of CO<sub>2</sub> emission with engine load is shown in figure 6. CO<sub>2</sub> is a parameter which indicates complete combustion of a fuel and its efficiency inside the combustion chamber [45]. The CO<sub>2</sub> emissions increased with load for all biodiesel blend and diesel fuel. The overall CO<sub>2</sub> emissions of B10, B20, B30, B75 and B100 were higher than that of diesel by 0.29%, 0.99%, 2.22%, 3.92% and 5.11% at 100% load of the engine. As blend increases there is an increase in CO<sub>2</sub> emissions due to the higher oxygen content of biodiesel which results in better combustion [46]. An increase in CO<sub>2</sub> emissions of soybean biodiesel was observed by Randazzo and Sodr  [47] with the increase of biodiesel percentage in blend. Similar results were observed by other researchers [48,49].

The emission of unburned hydrocarbon (HC) results depends on the combustion efficiency. If combustion is improved HC decrease and vice versa. Variation of HC emission in p.p.m. for all the tested fuels versus load is presented in Figure 7. The average HC emission for B10, B20, B30, B75

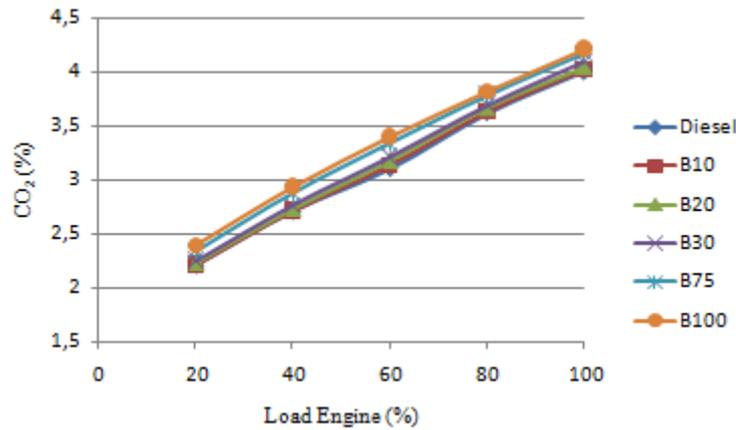


Figure 6. Variation in CO<sub>2</sub> emission with load.

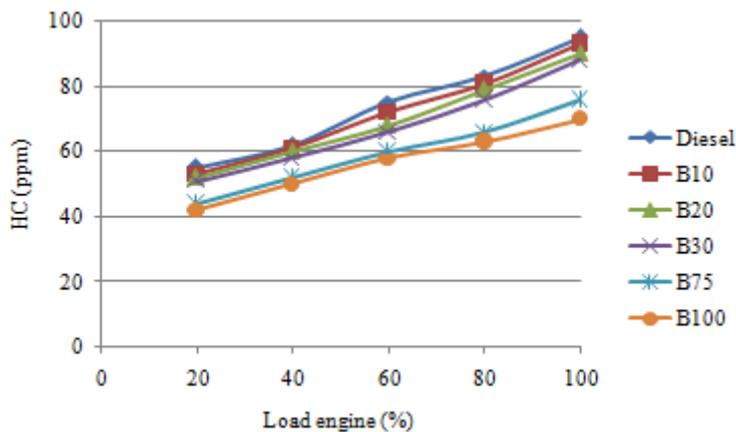


Figure 7. Variation in HC emission with load.

and B100 were less than that of diesel by 2.12%, 5.40%, 7.65%, 22.2%, and 30.30% at 100% load of the engine. Since biodiesel contains more oxygen in his structure and has a higher cetane number, the emissions of HC will decrease with the use of biodiesel blends. Amarnath and Prabhakaran [50] found that biodiesel of karanja and blends from 20% to 100%, reduce emissions of HC with 50% due to the better combustion. Sahoo et al. [51] found a reduction in HC emissions of neat karanja, jatropha and polanga biodiesels of 20.64%, 20.73% and 6.75%.

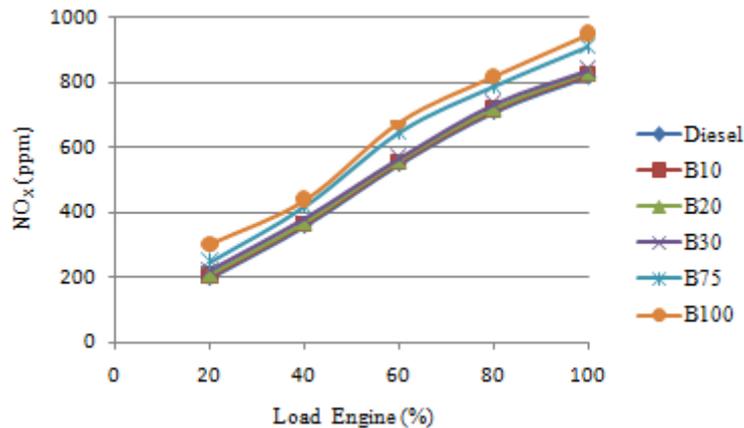


Figure 8. Variation in NO<sub>x</sub> emission with load.

Figure 8 exhibits the variation in NO<sub>x</sub> emission with load for B100, B75, B30, B20, B10 and diesel. The NO<sub>x</sub> formation depends of combustion temperature and oxygen content. The NO<sub>x</sub> emission level increases with load due to higher cylinder pressure and temperature for all blends of biodiesel and diesel. The overall increase in NO<sub>x</sub> emissions for biodiesels blends (B10, B20, B30, B75 and B100) were 0.72%, 1.21%, 2.40%, 10.4% and 14.68%, respectively, when compared with diesel fuel at full load. The results obtained in the tests are in concordance with the reports of other researchers that found a higher NO<sub>x</sub> emission due to higher oxygen content, higher specific fuel consumption and higher viscosity of biodiesel[52,53]. Aydin and İlkiliç [54] tested biodiesel of rapeseed and found an increase of NO<sub>x</sub> with 16.7% for B20 and 11.8% for B100.

#### 4. Conclusion

In the present work several tests were carried out on a single cylinder air cooled direct injection diesel engine using diesel, walnut biodiesel and different blends under various engine loads. The characterization of biodiesel blends prepared by alkaline-catalyzed transesterification process has shown that properties are comparable with diesel fuel. From the test the following conclusions have been drawn:

- Brake thermal efficiency decrease with increase in biodiesel percentage and is lower in the case of walnut biodiesel;
- Brake specific fuel consumption and exhaust gas temperature was found highest for pure biodiesel. This may be due to the high density, high volatility and high oxygen content of biodiesel;
- CO and HC emissions are highest for diesel fuel and lowest for biodiesel blends with high content of biodiesel because of higher oxygen content;
- CO<sub>2</sub> and NO<sub>x</sub> were found highest for diesel because of high combustion temperature of biodiesel.

#### 5. References

- [1] Yaakob Z, Mohammad M, Alherbawi M, Alam Z, Sopian K 2013 Overview of the production of biodiesel from waste cooking oil *Renew Sustain Energy Rev* pp 184-193
- [2] Wu X, Leung D Y 2018 Optimization of biodiesel production from camelina oil using orthogonal experiment *Appl Energy* **88** pp 3615-3624
- [3] Boyang Wang S L, Tian Songjiang, Feng Rihua, Meng Yonglu 2013 A new solid base catalyst for the transesterification of rapeseed oil to biodiesel with methanol *Fuel* **104** pp 698-703
- [4] Agarwal A K, Dhar A 2012 Wear, durability, and lubricating oil performance of a straight vegetable oil (Karanja) blend fueled direct injection compression ignition engine *J Renew Sustain Energy* 4(6) pp 063-138
- [5] Sharma Y C, Singh B, Upadhyay S N 2008 Advancements in development and characterization of biodiesel: a review *Fuel* **87** pp 2355-2373
- [6] Diasa J M, Araújo J M, Costa J F, Alvim-Ferraz M C M, Almeida M F 2013 Biodiesel production from raw castor oil *Energy* **53** pp 58-66
- [7] Zhang Y, Van Gerpen J H 1996 Combustion analysis of esters of soybean oil in a diesel engine. SAE Paper No. 960765 Warrendale PA SAE
- [8] Berti M R, Wilckensa S, Fischera, Solis A, Johnson B 2011 Seeding date influence on camelina seed yield, yield components, and oil content *Chile Ind Crops Prod* **34** pp 1358-1365
- [9] Demirbas A 2007 Biodiesel from sunflower oil in supercritical methanol with calcium oxide. *Energy Convers Manage* **48** pp 937-941
- [10] Mekhilefa S, Sigaa R S S 2011 A review on palm oil biodiesel as a source of renewable fuel *Renew Sustain Energy Rev* **15** pp 1937-1949
- [11] Saka S, Kusdiana D 2001 Biodiesel fuel from rapeseed oil as prepared in supercritical methanol. *Fuel* **80** pp 225-231
- [12] Keera S T, El Sabagh S M, Taman A R 2011 Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst *Fuel* **90** pp 42-47
- [13] Meher L, Vidya Sagar, Naik S 2006 Technical aspects of biodiesel production by

- transesterification – a review *Renew Sustain Energy Rev* **10** pp 248-68
- [14] Rao P S, Gopalkrishnan K V 1991 Vegetable oils and their methyl esters as fuel in diesel engines *Indian J Technol* **29** pp 292-297
- [15] Qi D H, Geng L M, Chen H, Bian Y Z H, Liu J, Ren X C H 2009 Combustion and performance evaluation of a diesel engine fuelled biodiesel produced from soybean crude oil *Renew Energy* **34** pp 2706-2713
- [16] Rizwanul Fattah I M, Masjuki H H, Liaquat A M, Ramli R, Kalam M A, Riazuddin V N 2013 Impact of various biodiesel fuels obtained from edible and non-edible oils on engine exhaust gas and noise emissions *Renew Sustain Energy Rev* **18** pp 552-567
- [17] Rao G L N, Nallusamy N, Sampath S, Rajagopal K 2008 Combustion and emission characteristics of diesel engine fuelled with methyl esters of pungam oil and rice bran oil *Int J Glob Energy Issues* **29** pp 314–328
- [18] Moigradean D, Poiana M A, Alda L M, Gogoasa I 2013 Quantitative identification of fatty acids from walnut and coconut oils using GC-MS method *Journal of Agroalimentary Processes and Technologies* **19** pp 459-463
- [19] Kostik V, Memeti S, Bauer B 2012 Fatty acid composition of edible oils and fats *Journal of Hygienic Engineering and Design* **4** pp 112-116
- [20] Amaral J S, Casal S, Pereira J A, Seabra R M, Oliveira B P 2003 Determination of sterol and fatty acid compositions, oxidative stability, and nutritional value of six walnut (*Juglans regia* L) cultivars grown in Portugal *Journal of Agricultural and Food Chemistry* **51** pp 7698-7702
- [21] National Institute of Statistics <http://www.insse.ro/cms/en>
- [22] Hu Hai-fang, Liu Weng-Jie, Zhang Qiang 2011 The Research on Prepared Walnut Biodiesel by Interesterification *Xinjiang Agricultural Sciences* **48** pp 1217-1221
- [23] Bryan R. Moser 2012 Preparation of fatty acid methyl esters from hazelnut, high-oleic peanut and walnut oils and evaluation as biodiesel *Fuel* **92** pp 231-238
- [24] Rasheda M M, Kalama M A, Masjukia H H, Mofijurb M, Rasulb M G, Zulkifli N W M 2016 Performance and emission characteristics of a diesel engine fueled with palm, jatropha, and moringa oil methyl ester *Industrial Crops and Products* **79** pp 70-76
- [25] Habibullah M, Masjuki H H, Kalam M A, Rizwanul Fattah I M, Ashraful A M, Mobarak H M 2014 Biodiesel production and performance evaluation of coconut, palm and their combined blend with diesel in a single-cylinder diesel engine *Energ Convers Manage* **8** pp 250-257
- [26] Khiari K, Awad S, Loubar K, Tarabet L, Mahmoud R, Tazerout M 2016 Experimental investigation of pistacia lentiscus biodiesel as a fuel for direct injection diesel engine *Energ Convers Manage* **108** pp 392-399
- [27] Ry 50 manual [http://www.lombardini.no/ruggerini/Datablad/Ry\\_50\\_uk.pdf](http://www.lombardini.no/ruggerini/Datablad/Ry_50_uk.pdf)
- [28] Technical specifications Stargas 898 [http://www.dijagnostika-vozila.rs/assets/files/Pdf/Kategorije/SPX\\_OTC/STARGAS/OTC\\_stargas\\_eng.pdf](http://www.dijagnostika-vozila.rs/assets/files/Pdf/Kategorije/SPX_OTC/STARGAS/OTC_stargas_eng.pdf)
- [29] Sahoo P K, Das L M 2009 Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine *Fuel* **88** pp 994-999
- [30] Chauhan B S, Kumar N, Cho H M, Lim H C 2013 A study on the performance and emission of a diesel engine fuelled with Karanja biodiesel and its blends *Energy* **56** pp 1-7
- [31] Banapurmath N R, Tewari P G, Kumar V V 2009 Combustion and emission characteristics of a direct injection CI engine when operated on Marotti oil methyl ester and blends of Marotti oil methyl ester and diesel *Int J Sustain Eng* **2(3)** pp 192-200
- [32] Rao G L N, Prasad B D, Sampath S, Rajagopal K 2007 Combustion analysis of diesel engine fuelled with jatropha oil methyl ester-diesel blends *Int J Green Energy* **4** pp 645-658
- [33] Jindal S, Nandwana B P, Rathore N S 2010 Comparative evaluation of combustion, performance, and emissions of Jatropha methyl ester and karanja methyl ester in a direct injection diesel engine *Energy Fuels* **24** pp 1565-1572
- [34] Wang X, Ge Y, Yu L, Feng X 2013 Comparison of combustion characteristics and brake thermal efficiency of a heavy-duty diesel engine fueled with diesel and biodiesel at high

- altitude *Fuel* **107** pp 852-858
- [35] Ono M, Nakajima M, Yoshida K, Shoji H, Iijima A Influence of Various Biodiesel Fuels on Diesel Engine Performance SAE Technical Paper 2009-32-0100
- [36] McCarthy P, Rasul M G, Moazzem S 2011 Analysis and comparison of performance and emissions of an internal combustion engine fuelled with petroleum diesel and different biodiesels *Fuel* **90** pp 2147-2157
- [37] Utlua Z, Kocak M S 2008 The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions *Renew Energy* **33** pp 1936–1941
- [38] Behcet R 2011 Performance and emission study of waste anchovy fish biodiesel in a diesel engine *Fuel Process Technol* **92** pp 1187-1194
- [39] Puhan S, Vedaraman N, Ram B V B, Sankarnarayanan G, Jeychandran K 2005 Mahua oil (*Madhuca indica* seed oil) methyl ester as biodiesel-preparation and emission characteristics *Biomass Bioenergy* **28** pp 87-93
- [40] Godiganur S, Murthy C H S, Reddy R P 2009 Cummins engine performance and emission tests using methyl ester mahua (*Madhuca indica*) oil/diesel blends *Renew Energy* **34** pp 2172-2177
- [41] Buyukkaya E 2010 Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics *Fuel* **89(10)** pp 3099-3105
- [42] Vedaraman N, Puhan S, Nagarajan G, Velappan K C 2011 Preparation of palm oil biodiesel and effect of various additives on NOx emission reduction in B20: an experimental study *Int J Green Energy* **8** pp 383-397
- [43] Raheman H, Phadatare A G 2004 Diesel engine emissions and performance from blends of karanja methyl ester and diesel *Biomass Bioenergy* **27** pp 393-397
- [44] Subbaiah G V, Gopal K R 2011 An experimental investigation on the performance and emission characteristics of a diesel engine fuelled with rice bran bio- diesel and ethanol blends *Int J Green Energy* **8** pp 197-208
- [45] Arbab M I, Masjuki H H, Varman M, Kalam M A, Imtenan S, Sajjad H 2013 Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel *Renew Sust Energy Rev* **22** pp 133-147
- [46] Gumus M 2010 A comprehensive experimental investigation of combustion and heat release characteristics of a biodiesel (hazelnut kernel oil methyl ester) fuelled direct injection compression ignition engine *Fuel* **89** pp 2802-2814
- [47] Randazzo M L, Sodre J R 2011 Exhaust emissions from a diesel powered vehicle fuelled by soybean biodiesel blends (B3–B20) with ethanol as an additive (B20E2–B20E5) *Fuel* **90** pp 98-103
- [48] Srivastava P K, Verma M 2007 Methyl ester of Karanja oil as alternative renewable source energy *Fuel* **87** pp 1673-1677
- [49] Lapuerta M, Armas O, Rodriguez-Fernandez J 2008 Effect of biodiesel fuels on diesel engine emissions *Prog Energy Combust Sci* **34** pp 198-223
- [50] Amarnath H K, Prabhakaran P 2012 A study on the thermal performance and emissions of a variable compression ratio diesel engine fuelled with karanja biodiesel and the optimization of parameters based on experimental data *Int J Green Energy* **9** pp 841-63
- [51] Sahoo P K, Das L M, Babu M K G, Arora P, Singh V P, Kumar N R, Varyani T S 2009 Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine *Fuel* **88** pp 1698-1707
- [52] Adi G, Hall C, Snyder D, Bunce M, Satkoski C, Kumar S, et al. 2009 Soy-biodiesel impact on NOx emissions and fuel economy for diffusion-dominated combustion in a turbo\_diesel engine incorporating exhaust gas recirculation and common rail fuel injection *Energy Fuels* **23** pp 5821-5829
- [53] Hess M A, Haas M J, Foglia T A 2007 Attempts to reduce NOx exhaust emissions by using reformulated biodiesel *Fuel Process Technol* **8** pp 693-699

- [54] Aydin H, İlkiliç C 2011 Exhaust emissions of a CI engine operated with biodiesel from rapeseed oil *Energy Sources Part A* **33** pp 1523-1531