Engineering Science and Technology, an International Journal 24 (2021) 631–636

HOSTED BY

ELSEVIER

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Environmental pollution cost analysis of a diesel engine fueled with biogas-diesel-tire pyrolytic oil blends

Nuri Tunç [a,*], Mustafa Karagöz [b], Burak Çiftçi [b], Emrah Deniz [c]

[a] Department of Mechanical Engineering, Institute of Science, Karabuk University, 78050 Karabuk, Turkey
[b] Automotive Technologies Program, TOBB Vocational School of Technical Sciences, Karabuk University, 78050 Karabuk, Turkey
[c] Faculty of Engineering, Department of Mechanical Engineering, Karabuk University, 78050 Karabuk, Turkey

ARTICLE INFO

Article history:
Received 25 June 2020
Revised 11 October 2020
Accepted 30 October 2020
Available online 15 November 2020

Keywords:
Environmental pollution cost analysis
Biogas
Tire pyrolytic oil

ABSTRACT

Fuels obtained from waste in seeking of sustainable and environmentally friendly fuel are promising for internal combustion engines. In this study, an environmental pollution cost analysis was performed for a diesel engine fueled with blends of pyrolytic oil – biogas - neat diesel fuel. Five different test fuels were studied. Neat diesel fuel (DF), the fuel mixture prepared by blending 10% pyrolytic oil to 90% neat diesel fuel by volume (DF90P10). While the DF90P10 fuel was supplied to the engine from the injector, the experiments were carried out with different fuel combinations created by delivering gaseous biogas at constant flow rates of 1, 3 and 5 L/min from the intake manifold (DF90P10B1, DF90P10B3, DF90P10B5). The experiments were carried out in a single-cylinder, air-cooled, direct injection diesel engine, with a constant engine speed of 3000 rpm and four different engine loads ranging from 0.25 to 1 kW, with prepared fuel blends. Fuel consumption, exhaust emissions, exhaust and engine block temperatures were measured to make environmental pollution cost analysis. In these tests, it was found that the DF90P10B1 test fuel performs better results as compared to those of neat diesel fuel which is reference fuel and other test fuels in terms of environmental pollution cost analysis. Pyrolytic oil – biogas – diesel fuel mixtures in variable ratios, can be used as an alternative fuel instead of neat diesel in diesel engines without any engine modifications.

© 2020 Karabuk University. Publishing services by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Increasing world population and rapid industrialization are growing the modern economy and causing more energy demand [1]. Depletion of non-renewable fuel sources, increase in the energy prices and endless exhaust emission pollution caused by internal combustion engines make researchers to be more interested in sustainable and environmentally friendly renewable energy sources. Alternative fuels are being explored to reduce the harmful effects of fuels and their derivatives, which are the basic energy sources required for production [2–14]. As an environmental problem; responsible for greenhouse gas emission and solid waste disposal (end-of-life tires) problems is the rapid growth in the number of vehicles powered by fossil fuels in parallel with the population increase [15]. Wastes made up of used tires, when exposed to sunlight and rainwater due to their non-degradable polymer structure naturally, cause significant environmental problems worldwide by leaking chemicals into the soil and air [16–18]. Recycling of waste tires by cutting or shredding them and making new products such as liquid tanks, mats, road floors, playground covers, sports fields is the best method in terms of economic and environmental results [19]. Another recycling method is to obtain coal, gas and valuable oil products as a result of pyrolysis of waste tires. These valuable oils are successfully used in engines due to their light fuel-like fuel properties [20]. Pyrolysis has become important due to its suitability for use in compression ignition (CI) engines to evaluate different wastes as an alternative fuel and to facilitate waste management [21]. As a result, pyrolysis is the best way to recycle waste tires [22].

Doğan et al. [23] prepared different test fuel mixtures by mixing the fuel obtained from tires (TDF) and diesel fuel in different volumetric ratios and tested these fuels in a diesel engine and examined the engine performance and emission values. As a result, they reported that with the increase of TDF content in fuel, unburned hydrocarbon (HC) and carbon monoxide (CO) emission values decreased, nitrogen oxide (NO) emissions increased, and addition of TDF to diesel fuel had no significant effect on engine performance values. Sharma et al. [24] in their experimental study,

* Corresponding author.
E-mail address: tunckar.nt@gmail.com (N. Tunç).
Peer review under responsibility of Karabuk University.

https://doi.org/10.1016/j.jestch.2020.10.008
2215-0986/© 2020 Karabuk University. Publishing services by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

examined the combustion, performance, and emission characteristics of the engine by using the mixture of tire pyrolysis oil (TPO) and Jatropha Methyl Ester (JME) as fuel in a one cylinder 4 stroke air cooled DI diesel engine. They reported that the engine combustion and emission behavior of the fuel with a mixture ratio of more than 20% TPO deviates, and there is a decrease of efficiency in the of 30%, 40% and 50% TPO blended fuels at full load. They stated that smoke emissions and CO, HC at full load are lower than diesel, and Nitric oxide emission at full load is approximately 24% higher for JME TPO20 compared to diesel. Hariharan et al. [25] used TPO as the main fuel and Diethyl ether (DEE) as the ignition enhancer auxiliary fuel in a one cylinder 4 stroke diesel engine and compared the performance, emission and combustion characteristics of the engine with diesel fuel (DF). The suction line was given DEE at three different (65, 130, 170 g/s) flow rates and consequently, they stated that with 170 g/s DEE, TPO fuel has lower emissions and better performance. They reported that at full load, TPO-DEE fuel NO_x emissions decreased by 5%, and HC, CO and smoke emissions were 2%, 4.5% and 38% higher respectively compared to DF fuel. Frigo et al. [26] mixed 20% and 40% waste tire oils (TPO20 and TPO40) in diesel fuel and carried out tests on the diesel engine. They compared the performance and emission values of the engine using diesel fuel together with the fuel mixes they prepared, and as a result, they reported that there was no significant difference in engine performance and emission values when using TPO20, but there was a deterioration in the combustion characteristics of the engine when using TPO40. Wang et al. [27] mixed the tire pyrolysis oil (TPO) they obtained, with neat diesel fuel and tested them for fuel consumption, cylinder pressure, engine power and SO_2 emissions in a DI diesel engine. As a result, they stated that increasing the tire pyrolysis oil fraction leads to poorer engine performance and higher sulfur dioxide (SO_2) emission. Kumaravel et al. [28] reported that TPO mixtures (TF5, TF10, TF25, TF35) can be used in engines without any modification. CO, HC, SO_2 and smoke emissions values were higher than diesel in high ratio (TF50, TF75, TF100) TPO-mixed fuel use. As a result, they stated that the oil obtained as a result of pyrolysis process from waste tires can be used as an alternative fuel in diesel engines after some processes (aromatic compounds and viscosity reduction). Baskovic et al. [29] reveal that using pure TPO in a turbocharged and intercooled diesel engine without using any auxiliary can provide more optimization of thermodynamic parameters by operating in a wide range. Singha et al. [30] subjected different plastic wastes to non-catalytic pyrolysis process at 450 °C to analyze the physical properties of the obtained product to obtain pyrolytic oil (PPO) similar to petroleum fuels. The obtained PPO has been mixed with diesel fuel in five different proportions (10, 20, 30, 40, 50%) and the performance characteristics of a diesel engine have been tested and as a result, they reported that the thermic efficiency increases when the PPO ratio in the mixture is increased; and specific fuel consumption decreases when the load is increased. They stated that PPO contains more Oxygenated compounds and as a result, it helps to decrease the emission values caused by combustion. Karagoz et al. [31] mixed TPO with pure diesel in volumes of 10% (TPO10 D90), 30% (TPO30 D70) and 50% (TPO50 D50) and tested with a one-cylinder, 4 stroke, naturally aspirated, compression-ignition diesel engine. As a result, they stated that the highest energy efficiency for all loads is with TPO10 D90 fuel. TPO diesel fuel mixture performance is better thermoeconomically and TPO-diesel blends are more suitable for sustainability. They also reported that TPO-diesel fuel mixtures can be used as a fuel additive in a CI Diesel engine without any modification.

In the literature, it was found that although the variables such as performance, combustion, vibration, noise and exhaust emissions caused by the use of waste tires from internal combustion engines were examined, there was no study on economical assessment of the environmental effects of carbon dioxide (CO_2) emissions. In this study, the environmental effects of carbon dioxide emissions resulting from the use of diesel/pyrolytic oil/biogas fuel blends in a diesel engine, at a constant crankshaft speed (3000 rpm), with different engine loads (0.25, 0.5, 0.75 and 1 kW) were examined economically, and environmental pollution cost analyses were carried out.

2. Material method

2.1. Engine experiment

Test fuel mixed with diesel fuel in this study can be given as a good example to waste energy form. Because the test fuels used in the study are pyrolytic fuel obtained from the waste vehicle tire and biogas that can be obtained from organic wastes by various methods. The first test fuel is neat diesel (DF). The other fuel which is formatted for this study is DF90P10 consisting of 90% pure diesel and 10% pyrolytic oil by volume. While this prepared fuel was supplied to the engine from the injector, the biogas was fed from the intake manifold of the engine at a flow rate of 1, 3 and 5 L/min. So, three new fuel mixtures were formed. These fuel combinations created were named DF90P10B1, DF90P10B3, DF90P10B5, respectively. Biogas flow rate of 1, 3 and 5 L/min was kept constant at all engine loads [33], and consumption of D90P10 test fuel varied according to engine load. The basic properties of the main test fuels are given in Table 1. The test fuels were obtained from commercial oil suppliers. The biogas used is in the form of a pressurized tube with 65% methane (CH_4) content and was supplied from a commercial enterprise [32].

DF90P10 fuel was mixed by volume. The amount of fuel consumed by the engine was determined using a stopwatch and a precision balance. Biogas is added to the intake air by making a special connection to the intake manifold. The amount of the biogas sent to the engine was determined using a mass meter (Newflow). The biogas flow rate was controlled by a valve added to the gas fuel line. The technical features of the test engine are presented in Table 2. A one cylinder, 4 stroke, naturally aspirated, air cooled diesel-generator set was used in the experiments.

CO_2 emission amounts were determined with an exhaust gas analyzer (Bilsa brand MOD 2210) connected to the exhaust outlet. The exhaust analyzer is capable of measuring CO_2 emissions in the range of 0–20 % with 0.001% accuracy. The scheme of the experiment set is given in Fig. 1.

2.2. Methodology

Environmental pollution cost analysis, which is an environmental economy model, is the economic and environmental costing of carbon dioxide. In this costing process, emitted carbon dioxide ratios are determined first, and then environmental pollution cost is found by using the carbon dioxide cost (0.0327 $/kg) calculated in previous studies [34,35]. (SEP_C) formula is used for specific Environmental Pollution cost calculation [34].

$$SEP_C\ (/kWh) = C_{CO_2} e_{CO_2} \tag{1}$$

Table 1
Basic characteristics of main test fuels.

Property	Diesel	Pyrolytic fuel	Biogas
Test fuel density (@15 °C, kg/m^3)	835.4	904	1.16
Test fuel viscosity (cSt,@40 °C)	2.93	5.04	–
Lower heating value (kJ/kg)	45975	40940	32500
Fuel component	%100	%100	%65CH_4 %35CO_2

Table 2
Technical features of the test engine.

Brand and model	Katana-KM178F
General features	DI diesel engine, Naturally-aspirated, Air-cooled.
Cylinder number	1
Power (kW @3000 rpm)	4
Displacement (cm^3)	296
Compression ratio	18:1
Bore × stroke (cm)	7.8x6.2
Injection nozzle	0.22 × 4 holes × 160°
Nozzle opening pressure (bar)	205

where, C_{CO2} is the cost of carbon dioxide emission, e_{CO2} is the emission of CO_2 emitted by the engine. The calculation of Total cost of pollution (TEP_C) ($), which is the CO_2 cost emitted by an diesel engine during its working life, can be expressed as [36];

$$TEP_C\ (\$) = C_{CO_2}(e_{CO_2}PNt) \tag{2}$$

where, t is the total service life of the engine (20 years), N is annual working hours (8000 h/y), P: is the crankshaft output power.

The formula (TEP_{LC}) ($), which is the Life cycle based total cost of pollution calculation, is used to calculate the cost of CO_2 and fuel emitted during the working life of the diesel engine [37].

$$TEP_{LC}\ (\$) = C_{CO_2}[(e_{CO_2}PNt) + (m_{ICE}e_{ICE}) + (\dot{Q}_F e_F Nt)] \tag{3}$$

where, m_{ICE} is the mass of engine (86 kg), e_{ICE} is the emission rate of internal combustion engine material (considered to be 3.012 (kCO_2/kg) [33]), Q_F is the heat energy of fuel (kJ/h), and e_F is emission from the production process of the fuel.

For the pyrolytic oil -diesel-biogas mixture fuel, the emission caused by the fuel production process; pyrolytic oil in the pyrolytic oil - diesel - biogas blend, clean diesel and biogas mass fractions were calculated as [34]:

$$e_F = \frac{\dot{m}_D e_{F,DF} + \dot{m}_P e_{F,P} + \dot{m}_B e_{F,B}}{\dot{m}_D + \dot{m}_P + \dot{m}_B} \tag{4}$$

where, e_F is the emission from the production process of the fuel and was calculated as;

– 0.083 $kgCO_2$/MJ for pure diesel
– 0.082 $kgCO_2$/MJ for pyrolytic oil
– 0.032 $kgCO_2$/MJ for biogas [30,31].

The Life Cycle Specific Environmental Pollution Cost calculation (SEP_{LC}) is made by [34];

$$SEP_{LC}\left(/kWh\right) = \frac{TEP_{LC}}{(PNt)} \tag{5}$$

The formula (£) is used to calculate the total CO_2 emission parameter [36];

$$£ = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \tag{6}$$

where, m_{CO2} is the Mass flow rate of carbon dioxide (kg/s), is the net work output of the test engine (kJ).

Formula (PP) is used to calculate the total payback period of the test engine system [36];

$$PP = \frac{4.3(PEC + OM)}{N(\dot{W}_{net}c_{el} + \dot{Q}_f c_f)} \tag{7}$$

where, PEC is the cost of equipment purchased ($), OM is the operation and maintenance cost ($), c_{el} is the cost of electricity ($/kWh), and c_f is the fuel price ($/kWh).

(EPP) (year) formula is used for environmental payback period calculation [36];

$$EPP = \frac{TEP}{N\dot{W}_{net}c_{el}} \tag{8}$$

(EPPLC) formula is used for environmental payback period calculation based on life cycle [36];

$$EPP_{LC} = \frac{TEP_{LC}}{N\dot{W}_{net}c_{el}} \tag{9}$$

Test fuel costs used are given in the Table 3. The test engine cost 1100 $. The unit price for electricity was = 0.1212 $/kWh [38].

Maintenance and operation cost of the engine used in the experiments has been accepted as 1.092% of the purchase cost of the equipment [39].

3. Results and discussion

In this study, environmental pollution cost analysis was performed using diesel, DF90P10, DF90P10B1, DF90P10B3, DF90P10B5 fuel and fuel blends in an experimental engine setup under the loads of 0.25, 0.5, 0.75 and 1 kW. The one cylinder, naturally aspirated, 4 stroke, internal combustion CI diesel engine used in the experimental setup was run at constant speed of 3000 L/min.

In the experiments, CO_2 emissions and effective power results of the test engine for pyrolytic oil - diesel biogas mixed fuels were calculated and given in Table 4.

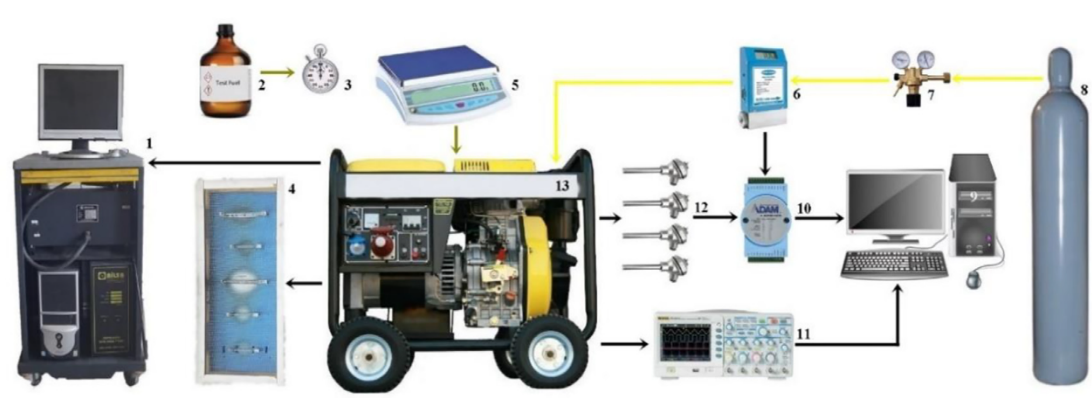

Fig. 1. The scheme of the experimental set.

Table 3
Test fuels costs.

Fuel	Load (kW)	Cost ($/kJ)
Diesel	–	2.060 *10^{-5}
DF90P10	–	1.976 *10^{-5}
DF90P10B1	0.25	2.379 *10^{-5}
DF90P10B1	0.50	2.277 *10^{-5}
DF90P10B1	0.75	2.220 *10^{-5}
DF90P10B1	1	2.172 *10^{-5}
DF90P10B3	0.25	3.217 *10^{-5}
DF90P10B3	0.50	2.969 *10^{-5}
DF90P10B3	0.75	2.776 *10^{-5}
DF90P10B3	1	2.622 *10^{-5}
DF90P10B5	0.25	4.211 *10^{-5}
DF90P10B5	0.50	3.766 *10^{-5}
DF90P10B5	0.75	3.375 *10^{-5}
DF90P10B5	1	3.116 *10^{-5}

Table 4
CO_2 emission values of experiment set engine. (e_{CO2}: CO_2 emission values *(kg/kWh).)*

Test Fuel	*Load (kW)*			
	0.25	*0.50*	*0.75*	*1.0*
DF	2.6441	1.5422	1.1271	1.0695
DF90P10	2.6688	1.4867	1.1208	0.9543
DF90P10B1	2.6400	1.4793	1.0994	0.9435
DF90P10B3	3.6907	1.9914	1.4347	1.1490
DF90P10B5	4.4037	2.3292	1.6544	1.3065

As the experimental engine load increased, it was observed that the emitted CO_2 emissions decreased. The highest e_{CO2} value was observed in DF90P10B5 fuel blend as 4.4037 (kg/kWh) under 0.25 kW load, while the lowest e_{CO2} value was in the DF90P10B1 fuel blend as 0.9435 (kg/kWh) under 1.00 kW load. The highest e_{CO2} values for all loads were measured using the DF90P10B5 fuel blend, while the lowest e_{CO2} values for all loads were measured using the DF90P10B1.

The SEP_C, TEP_C, SEP_{LC} and TEP_{LC} values of experiment engine for pyrolytic oil - diesel - biogas fuel blends are given in Table 5.

The lowest SEP_C value for all loads was obtained to be 0.0309 $/kWh under 1.00 kW load with DF90P10B1 fuel blend, while the highest SEP_C value was 0.1440 $/kWh with DF90P10B5 fuel mixture under 0.25 kW load. The lowest and the highest SEP_C values under 0.25, 0.5, 0.75, 1 kW loads were observed in fuel blends DF90P10B1 and DF90P10B5 respectively.

The lowest TEP_C value for all loads was observed with DF90P10B1 blend as $ 3753.34 and the highest TEP_C value as $ 7430.10 with the DF90P10B5 fuel blend. TEP_C values of fuel blends are observed as DF90P10B1 < DF90P10 < Diesel < DF90P10B3 < D F90P10B5 for 0.50 kW and 0.75 kW loads; DF90P10B1 < Diesel < DF90P10 < DF90P10B3 < DF90P10B5 for 0.25 kW load; and DF90P10B1 < DF90P10 < Diesel < DF90P10B3 < DF90P10B5 for 1.00 kW load. The lowest TEP_C values for all loads were observed in the DF90P10B1 fuel mixture.

The lowest SEP_{LC} value for all loads was obtained as 0.1065 $/ kWh under 1.00 kW with the DF90P10B1 fuel blend, while the highest SEP_{LC} value was 0.3061 $/kWh with the DF90P10B5 fuel blend. The lowest TEP_{LC} value for all loads was $10272.67 under 0.25 kW load with the DF90P10B1 fuel blend, while the highest TEP_{LC} value was recorded as $21454.93 under 1.00 kW load with Diesel fuel.

The SEP_{LC} and TEP_{LC} values were calculated as DF90P10B1 < Diesel < DF90P10 < DF90P10B3 < DF90P10B5 under 0.25 kW and 0.75 kW loads; DF90P10 < DF90P10B1 < Diesel < D F90P10B3 < DF90P10B5 under 0.50 kW load and DF90P10B1 < D F90P10 < DF90P10B3 < DF90P10B5 < Diesel under 1 kW load. SEP_C < SEP_{LC} and TEP_C < TEP_{LC} were observed for all loads. The £, *PP, EPP* and EPP_{LC} values of the experiment set engine give in Table 6.

According to the results of the experiment, the lowest £ value for all cases was obtained as 2.6207 £ x10^{-4} (kg/kJ) under 1.00 kW load, with the DF90P10B1 blend; and the highest £ value was obtained as 12.2325 £ x10^{-4} (kg/kJ) under 0.25 kW load, with the DF90P10B5 blend. DF90P10B1 has the lowest values under 0.25, 0.5, 0.75, 1 kW loads, while DF90P10B5 blend has the highest values under all loads.

According to the calculations, it was observed that there was a decrease in the PP values when the loads increased for each fuel type. While PP values order is DF90P10B5 < DF90P10B3 < DF90 P10B1 < Diesel < DF90P10 under 0.25, 0.5, 0.75, 1 kW loads, the order is DF90P10B5 < DF90P10B3 < Diesel < DF90P10B1 < DF90

Table 5
The SEP_C, TEP_C, SEP_{LC}, and TEP_{LC} values of experiment set engine.

Test Fuel	*Load (kW)*	*SEP_C ($/kWh)*	*TEP_C ($)*	*SEP_{LC} ($/kWh)*	*TEP_{LC} ($)*
DF	0.25	0.0865	3759.25	0.2483	10794.91
DF	0.50	0.0504	4385.13	0.1519	13208.18
DF	0.75	0.0369	4807.41	0.1176	15336.09
DF	1	0.0350	6082.18	0.1234	21454.93
DF90P10	0.25	0.0873	3794.31	0.2523	10969.62
DF90P10	0.50	0.0486	4227.50	0.1479	12861.63
DF90P10	0.75	0.0367	4780.66	0.1187	15488.58
DF90P10	1	0.0312	5427.19	0.1071	18621.04
DF90P10B1	0.25	0.0863	3753.34	0.2363	10272.67
DF90P10B1	0.50	0.0484	4206.33	0.1481	12878.41
DF90P10B1	0.75	0.0359	4688.98	0.1175	15328.81
DF90P10B1	1	0.0309	5365.43	0.1065	18526.53
DF90P10B3	0.25	0.1207	5247.22	0.2787	12115.64
DF90P10B3	0.50	0.0651	5662.50	0.1614	14033.57
DF90P10B3	0.75	0.0469	6119.16	0.1251	16318.69
DF90P10B3	1	0.0376	6534.08	0.1092	18991.10
DF90P10B5	0.25	0.1440	6260.90	0.3061	13308.54
DF90P10B5	0.50	0.0762	6622.91	0.1727	15021.67
DF90P10B5	0.75	0.0541	7056.17	0.1332	17369.64
DF90P10B5	1	0.0427	7430.10	0.1136	19753.07

SEP_C: Specific environmental pollution cost (*$/kWh*).
TEP_C: Total environmental pollution cost (*$*).
SEP_{LC}: Life cycle specific environmental pollution cost (*$/kWh*).
TEP_{LC}: Total environmental pollution cost based on life cycle (*$*).

Table 6
The £, *PP*, *EPP* and EPP_{LC} values of the experiment set engine.

Test Fuel	Load (kW)	£ x 10^{-4} (kg/kJ)	PP (year)	EPP (year)	EPP_{LC} (year)
DF	0.25	7.3448	1.6316	14.2684	40.9725
DF	0.50	4.2838	1.2348	8.3220	25.0661
DF	0.75	3.1309	0.9996	6.0822	19.4029
DF	1	2.9708	0.6945	5.7713	20.3582
DF90P10	0.25	7.4133	1.6629	14.4015	41.6356
DF90P10	0.50	4.1298	1.3027	8.0228	24.4084
DF90P10	0.75	3.1135	1.0196	6.0484	19.5958
DF90P10	1	2.6509	0.8161	5.1498	17.6692
DF90P10B1	0.25	7.3332	1.3788	14.2459	39.9903
DF90P10B1	0.50	4.1091	1.0623	7.9826	24.4402
DF90P10B1	0.75	3.0538	0.873	5.9324	19.3937
DF90P10B1	1	2.6207	0.7191	5.0912	17.5795
DF90P10B3	0.25	10.2520	0.8465	19.9160	45.9854
DF90P10B3	0.50	5.5317	0.7541	10.7461	26.6325
DF90P10B3	0.75	3.9852	0.6660	7.7418	20.6461
DF90P10B3	1	3.1916	0.5835	6.2001	18.0203
DF90P10B5	0.25	12.2325	0.5650	23.7635	50.5131
DF90P10B5	0.50	6.4699	0.5406	12.5687	28.5076
DF90P10B5	0.75	4.5954	0.5042	8.9273	21.9757
DF90P10B5	1	3.6292	0.4656	7.0503	18.7434

£ x 10^{-4}: Total carbon dioxide emission parameter (*kg/kJ*).
PP: Total payback period of the test engine system (year).
EPP: Total environmental payback period (year).
EPP_{LC}: Total environmental payback period based on life cycle (year).

P10 under 1.00 kW load. The highest PP values under all loads were obtained with the DF90P10 fuel blend. The highest PP value was obtained with the DF90P10 fuel blend as 1.6629 PP (year) under 0.25 kW load and the lowest PP value was obtained with the DF90P10B5 fuel blend as 0.4656 PP (year) under the load of 1.00 kW.

According to the calculations, the lowest EPP values were obtained with DF90P10B1 fuel blend under 0.25, 0.5, 0.75, 1 kW loads. Considering all the loads, the highest EPP value under all loads was obtained with the DF90P10B5 fuel blend under 0.25 kW load as 23.7635 EPP (year), and the lowest EPP value was obtained as 5.0912 EPP (year) under 1.00 kW load with the DF90P10B1 fuel blend.

According to the calculations, the EPP_{LC} values are ordered as DF90P10B1 < Diesel < DF90P10 < DF90P10B3 < DF90P10B5 under loads of 0.25 kW/0.75 kW, while they ordered as DF90P10 < DF90P10B1 < Diesel < DF90P10B3 < DF90P10B5 under load of 0.50 kW and DF90P10B1 < DF90P10 < DF90P10B3 < DF90 P10B5 < Diesel under 1.00 kW load. The lowest EPP_{LC} value was obtained with DF90P10B1 fuel blend as 17.5795 EPPLC (year) under 1.00 kW load, while the highest EPP_{LC} value was obtained as 50,5131 EPP_{LC} (year) with DF90P10B5 fuel blend under 0.25 kW load.

Tables 5 and 6 show that the pyrolytic oil-diesel blend and fuel with low biogas content may have an advantage in terms of environmental pollution cost analysis for all parameters compared to neat diesel fuel and pyrolytic oil-diesel-biogas blends. This means that the DF90P10B1 performs better in terms of environmental pollution cost compared to neat diesel and other test fuels.

4. Conclusion

In this study, the environmental effects of carbon dioxide emissions resulting from the use of diesel/pyrolytic oil/biogas fuel mixture in a diesel engine, at a constant crankshaft speed (3000 rpm), with different engine loads (0.25, 0.5, 0.75 and 1 kW) were examined economically, and environmental pollution cost analyses were carried out. As a result of the measurements and calculations, the following conclusions can be drawn;

- According to the SEP_C, SEP_{LC}, TEP_C and TEP_{LC} results, DF90P10B1 fuel has lower values for all loads. Maximum values for Diesel (DF) and all other fuel blends were obtained at 1 kW load. According to these data, DF90P10B1 fuel is a better option than Diesel (DF) fuel according to SEP_C, SEP_{LC}, TEP_C, TEP_{LC} analysis results.
- According to the results obtained from the environmental pollution cost analysis, pyrolytic fuel-diesel blends with low biogas content performed better than pure diesel and pyrolytic fuel-diesel blends with high biogas content.
- CO_2 emissions decrease as engine load increases. The maximum CO_2 emission value was measured at 0.25 kW load with DF90P10B5 fuel blend. The DF90P10B1 fuel gives the best results in terms of CO_2 emissions compared to Diesel (DF) and other fuel blends. Finally, it can be said that biogas-pyrolytic fuel-diesel mixtures can be used as an alternative fuel instead of neat diesel in diesel engines without a modification.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by Research Funds of Karabük University (Project Number: FDT-2019-2097). As the authors, we deeply appreciate to Karabük University for their financial support.

References

[1] A. Gupta, J.P. Verma, Sustainable bio-ethanol production from agro-residues: a review, Renew. Sustain. Energy Rev. 41 (2015) 550–567, https://doi.org/10.1016/j.rser.2014.08.032.
[2] I.M. Yusri, R. Mamat, M.K. Akasyah, M.F. Jamlos, A.F. Yusop, Evaluation of engine combustion and exhaust emissions characteristics using diesel/butanol blended fuel, Appl. Therm. Eng. 156 (2019) 209–219, https://doi.org/10.1016/j.applthermaleng.2019.02.028.
[3] G. Büyüközkan, S. Güleryüz, An integrated DEMATEL-ANP approach for renewable energy resources selection in Turkey, Int. J. Prod. Econ. 182 (2016) 435–448, https://doi.org/10.1016/j.ijpe.2016.09.015.

[4] P. Rani, A.R. Mishra, A. Mardani, F. Cavallaro, M. Alrasheedi, A. Alrashidi, A novel approach to extended fuzzy TOPSIS based on new divergence measures for renewable energy sources selection, J. Cleaner Prod. 257 (2020) 120352, https://doi.org/10.1016/j.jclepro.2020.120352.
[5] A. Elfasakhany, Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: Performance and emissions analysis, Engineering Science and Technology, an International Journal 18 (4) (2015) 713–719, https://doi.org/10.1016/j.jestch.2015.05.003.
[6] P. Baskar, A. Senthilkumar, Effects of oxygen enriched combustion on pollution and performance characteristics of a diesel engine, Engineering Science and Technology, an International Journal 19 (1) (2016) 438–443, https://doi.org/10.1016/j.jestch.2015.08.011.
[7] U. Rajak, T.N. Verma, Influence of combustion and emission characteristics on a compression ignition engine from a different generation of biodiesel, Engineering Science and Technology, an International Journal 23 (1) (2020) 10–20, https://doi.org/10.1016/j.jestch.2019.04.003.
[8] M. Karagoz, C. Uysal, U. Agbulut, S. Saridemir, Exergetic and exergoeconomic analyses of a CI engine fuelled with diesel-biodiesel blends containing various metal-oxide nanoparticles, Energy. 118830 (2020).
[9] S. Sarıdemir, A.E. Gürel, U. Ağbulut, F. Bakan, Investigating the role of fuel injection pressure change on performance characteristics of a DI-CI engine fuelled with methyl ester, Fuel 271 (2020) 117634.
[10] M. Karagöz, S. Sarıdemir, E. Deniz, B. Çiftçi, The effect of the CO2 ratio in biogas on the vibration and performance of a spark ignited engine, Fuel 214 (2018) 634–639, https://doi.org/10.1016/j.fuel.2017.11.058.
[11] Y. Kurtgoz, M. Karagoz, E. Deniz, Biogas engine performance estimation using ANN, Engineering Science and Technology, an International Journal 20 (6) (2017) 1563–1570, https://doi.org/10.1016/j.jestch.2017.12.010.
[12] Ü. Ağbulut, S. Sarıdemir, M. Karagöz, Experimental investigation of fusel oil (isoamyl alcohol) and diesel blends in a CI engine, Fuel 267 (2020) 117042, https://doi.org/10.1016/j.fuel.2020.117042.
[13] Ü. Ağbulut, S. Sarıdemir, A general view to converting fossil fuels to cleaner energy source by adding nanoparticles, International Journal of Ambient Energy (2019), https://doi.org/10.1080/01430750.2018.1563822.
[14] Ü. Ağbulut, S. Sarıdemir, S. Albayrak, Experimental investigation of combustion, performance and emission characteristics of a diesel engine fuelled with diesel–biodiesel–alcohol blends, J Braz. Soc. Mech. Sci. Eng. 41 (9) (2019), https://doi.org/10.1007/s40430-019-1891-8.
[15] Worldwide Motorization Rate 2015 - OICA (International Organization of Motor Vehicles Manufacturers). (2018), http://www.oica.net/world-vehicles-in-use-all-vehicles-2/.).
[16] R. Idris, C.T. Chong, F.N. Ani, Microwave-induced pyrolysis of waste truck tires with carbonaceous susceptor for the production of diesel-like fuel, J. Energy Inst. 92 (2019) 1831–1841, https://doi.org/10.1016/j.joei.2018.11.009.
[17] X. Shu, B. Huang, Recycling of waste tire rubber in asphalt and portland cement concrete: An overview, Constr. Build. Mater. 67 (2014) 217–224, https://doi.org/10.1016/j.conbuildmat.2013.11.027.
[18] C. Constantinescu, Ecological Dimension of Tire Management, Environmental Impact of tire use, International Journal of Academic Research in Accounting, Finance and Management Sciences. 2 (2012) 187–195.
[19] E.B. Machin, D.T. Pedroso, J.A. de Carvalho Jr., Energetic valorization of waste tires, Renew. Sustain. Energy Rev. 68 (2017) 306–315, https://doi.org/10.1016/j.rser.2016.09.110.
[20] P.T. Williams, Pyrolysis of waste tires: A review, Waste Manage. 33 (2013) 1714–1728, https://doi.org/10.1016/j.wasman.2013.05.003.
[21] A.K. Das, D. Hansdah, A.K. Mohapatra, A.K. Panda, Energy, exergy and emission analysis on a DI single cylinder diesel engine using pyrolytic waste plastic oil diesel blend, J. Energy Inst. 93 (4) (2020) 1624–1633, https://doi.org/10.1016/j.joei.2020.01.024.
[22] S. Arya, A. Sharma, M. Rawat, A. Agrawal, Tire pyrolysis oil as an alternative fuel: A review, Mater. Today:. Proc. (2020), https://doi.org/10.1016/j.matpr.2020.04.797.
[23] O. Doğan, M.B. Çelik, B. Özdalyan, The effect tirederivedfuel-diesel fuel blends utilization dieselengineemissions, Fuel 95 (2012) 340–346, https://doi.org/10.1016/j.fuel.2011.12.033.
[24] A. Sharma, S. Murugan, Investigation on the behavior of a DI diesel engine fueled with Jatropha Methyl Ester (JME) and Tire Pyrolysis Oil (TPO) blends, Fuel 108 (2013) 699–708, https://doi.org/10.1016/j.fuel.2012.12.042.
[25] S. Hariharan, S. Murugan, G. Nagarajan, Effect of diethyl ether on Tire pyrolysis oil fueled diesel engine, Fuel 104 (2013) 109–115, https://doi.org/10.1016/j.fuel.2012.08.041.
[26] S. Frigo, M. Seggiani, M. Puccini, S. Vitolo, Liquid fuel production from waste tyre pyrolysis and its utilisation in a Diesel engine, Fuel 116 (2014) 399–408, https://doi.org/10.1016/j.fuel.2013.08.044.
[27] W.-C. Wang, C.-J. Bai, C.-T. Lin, S. Prakash, Alternative fuel produced from thermal pyrolysis of waste tires and its use in a DI diesel engine, Appl. Therm. Eng. 93 (2016) 330–338, https://doi.org/10.1016/j.applthermaleng.2015.09.056.
[28] S.T. Kumaravel, A. Murugesan, A. Kumaravel, Tyre pyrolysis oil as an alternative fuel for diesel engines, Renew. Sustain. Energy Rev. 60 (2016) 1678–1685, https://doi.org/10.1016/j.rser.2016.03.035.
[29] U. Žvar Baškovič, R. Vihar, T. Seljak, T. Katrašnik, Feasibility analysis of 100% tire pyrolysis oil in a common rail Diesel engine, Energy 137 (2017) 980–990, https://doi.org/10.1016/j.energy.2017.01.156.
[30] R.K. Singh, B. Ruj, A.K. Sadhukhan, P. Gupta, V.P. Tigga, Waste plastic to pyrolytic oil and its utilization in CI engine: Performance analysis and combustion characteristics, Fuel 262 (2020) 116539, https://doi.org/10.1016/j.fuel.2019.116539.
[31] M. Karagoz, C. Uysal, Ü. Agbulut, S. Saridemir, Energy, exergy, economic and sustainability assessments of a compression ignition diesel engine fueled with tire pyrolytic oil diesel blends, J. Cleaner Prod. 264 (2020), https://doi.org/10.1016/j.jclepro.2020.121724 121724.
[32] HABAŞ (2020), https://www.habas.com.tr/Category/Alias/ozel-gazlar-.
[33] H. Ambarita, Performance and emission characteristics of a small diesel engine run in dual-fuel (diesel-biogas) mode, Case Studies in Thermal Engineering. 10 (2017) 179–191, https://doi.org/10.1016/j.csite.2017.06.003.
[34] I. Yildiz, E. Açıkkalp, H. Caliskan, K. Mori, Environmental pollution cost analyses of biodiesel and diesel fuels for a diesel engine, J. Environ. Manage. 243 (2019) 218–226, https://doi.org/10.1016/j.jenvman.2019.05.002.
[35] S.K. Ayaz, O. Altuntas, H. Caliskan, Thermoecologic Assessment and Life Cycle–Based Environmental Pollution Cost Analysis of Microgas Turbine, Journal of Environmental Engineering. January (2020), https://doi.org/10.1061/(ASCE)EE.1943-7870.0001611.
[36] B.B. Kanbur, L. Xiang, S. Dubey, F.H. Choo, F. Duan, Life cycle-based enviroeconomic and thermal analyses of the inlet air-cooled microturbine systems with liquefied natural gas cold energy, J. Cleaner Prod. 174 (2018) 1338–1350, https://doi.org/10.1016/j.jclepro.2017.11.046.
[37] P. Burke, Amounts of CO_2 Released when Making & Using, Products (2017). http://www.co2list.org/files/carbon.htm#range!a83.
[38] EPDK, Republic of Turkey Energy Market Regulatory Authority. 28 September (2019), www.epdk.org.tr.
[39] G. Tsatsaronis, J. Pisa, Exergoeconomic evaluation and optimization of energy systems-application to the CGAM problem, Energy 19 (1994) 287–321, https://doi.org/10.1016/0360-5442(94)90113-9.