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Well to Wheel: a Life-Cycle Based Analysis of CI Engine Powered with Diesel and Various Alcohol Blends

Ümit Ağbulut [1*]

0000-0002-6635-6494

[1] *Department of Mechanical Engineering, Faculty of Engineering, Duzce University, Düzce, 81620, Turkey*

Abstract

The core objective of the present research is to investigate the life cycle-based environmental analysis of a CI engine powered with diesel (DF), diesel (90%) and ethanol (10%) (E10), and diesel (90%) and methanol (10%) (M10) blends. The data is gathered when the engine runs at a constant engine speed of 1800 rpm, and varying engine loads from 2.5 Nm to 10 Nm with gaps of 2.5 Nm. In the results, higher CO_2 emissions are recorded when the engine is fed by E10 and M10 test fuels due to the worsening engine performance and high-oxygen content of relevant alcohols. Cumulatively, the CO_2 emission is higher 17.37% for E10 and 24.76% for M10 test fuel in comparison to that of DF. Given that the life cycle analysis, it is noticed that DF has respectable advantages. In comparison to that of conventional DF, life cycle based total environmental pollution cost of E10 and M10 test fuels is calculated to be higher by 4.13% and 8.61%, respectively. The highest specific life cycle-based environmental values are calculated to be 0.1371 \$/kWh, 0.1444 \$/kWh, and 0.1607 \$/kWh for DF, E10, and M10 test fuels at 2.5 Nm. The highest life cycle based environmental payback pollution values are achieved to be 22.62 years for DF, 23.83 years for E10, and 26.52 years for M10 test fuels at 2.5 Nm. In the conclusion, it is well-noticed that biofuels cannot compete with conventional DF in terms of economical and CO_2-based life cycle environmental pollution issues in today's technology.

Keywords: Life cycle analysis, CO_2 emissions, Ethanol, Methanol, Pollution cost

Research Article

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* Corresponding author

Ümit Ağbulut

umitagbulut@duzce.edu.tr

Address: Mechanical Engineering Department, Faculty of Engineering, Duzce University, 81620, Düzce, Turkey.

Tel: +903805421036-2285

Fax: +903805421037

1. Introduction

Undoubtedly, scientists have united on the idea that the consumption of fossil-based fuels is an overriding trigger of both environmental and economic problems for the government's in today's world. The reason underlying this idea is associated with the dominant use of fossil-based fuels in many sectors. For example, the transportation sector has been nowadays driven by the burning of fossil-based fuels at a respectable rate of more than 95% [1]. The dominant use of these fuels in the transport sector is currently equivalent to approximately half of the total global oil consumption [2]. As it is well known, fossil-based fuels highly pollute the environment [3-8]. For instance, nearly three kilograms of greenhouse gas emissions release into the atmosphere when one-kilogram of diesel fuel is burnt in the internal combustion engines [9]. These data obviously reveal how internal combustion engines can affect the levels of greenhouse gas emissions worldwide. According to the data reported by International Energy Agency, the transportation sector accounts for approximately 1/3 of global energy-related CO_2 emissions all across the World [10]. CO_2 emission is the highest share on the greenhouse gases all over the world, and its share on total greenhouse gases is gradually increasing [11-14]. For example, CO_2 emissions in Turkey is of 69% of total GHG emissions in the year 1990, and it reached by 80.5% in the year 2018 [15]. The similar increment trends on the share of CO_2 emission are also observed for other counties, too [16-21] For this reason, numerous governments have tried to take some concrete steps to mitigate the carbon emissions by dealing with different carbon-control mechanisms such as carbon taxes, cap-and-trade systems, carbon offsets, carbon caps, and eco-friendly technology norms [15, 22]. Out of these five mechanisms, the carbon tax is always the most popular one that directly sets prices on carbon content or carbon emissions of fossil-based fuels. However, as of 2019, there are only 26 countries that adopted the carbon tax. There has been a rapid increase in the number of countries adopting the carbon tax in recent years. That is, 17 of the 26 countries have started to apply the carbon tax after the year 2008 [15, 23]. On the other hand, eco-friendly technology norms have been, for example, implemented to the very limited fields in the technological industries such as carbon cap and carbon offsets, the automotive battery sectors. However, these industries have been counted to make a small impact on the mitigation of global carbon footprint [24]. With this framework, the fuel researchers as well as engine community are dedicated to reducing the CO_2 emissions arising from the internal combustion engines [25-32]. Accordingly, a plenty of biofuels as well as other solid particles and gases have been tested in the internal combustion engines, heretofore [33-39]. However, most of the studies to mitigate the CO_2 emissions from the engines in the literature focuses on the fuel-modification, and based on the first law of thermodynamics, as well as combustion and performance behavior of the engine [40-45]. On the other hand, CO_2 emissions arising from the steps of both the fuel processing history from well to wheel and engine-production history are generally ignored by the researchers and producers. Whereas, it is of great importance to know the emitted CO_2 emissions during these production steps. This is because a fuel and/or fuel mixture is considered more environmentally friendly when it causes less CO_2 emission when burned in an engine. However, this alone is not sufficient in deciding its environmental effect. The most important factor at this point is that how much it causes the emission when it is produced and how much it causes the emission when it is consumed. These two significant points should be well handled together. In recent years, life cycle-based environmental analysis of CO_2 emission arising from internal combustion engines has been, therefore, attracted attention from the fuel researchers [46-50]. Schematically, a general life cycle of conventional diesel fuel based on the well to wheel concept is depicted in Figure 1.

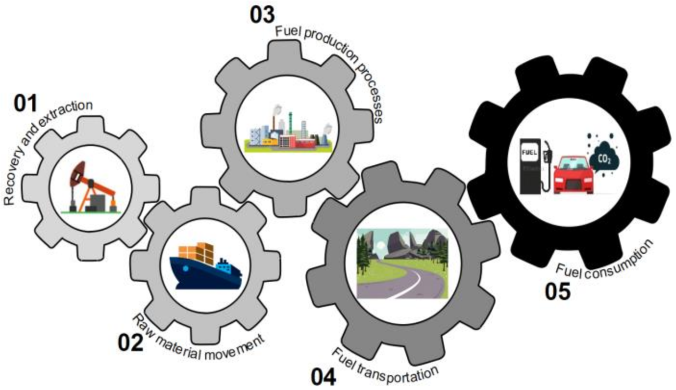

Fig. 1. Steps of the well-to-wheel and life cycle CO_2 emissions.

Many studies available in the literature are concerned with the exhaust emissions released in the post-combustion. However, the amount of emissions in the production stages of these fuels, from the extraction and processing of these fuels to the end-user, is generally ignored. Whereas, it is a highly important issue to know the impact of fuels on the environment during their production as well as the emissions they emit after their use. In this framework, this study offers a detailed life cycle analysis, taking into account the fuels' historical production processes. In the present research, life cycle based environmental and enviroeconomic assessments of CO_2 emissions are studied according to the environmental pollution analysis approach. The experiments are performed when the engine fueled with completely diesel fuel and diesel-ethanol and diesel-methanol binary blends, separately. In the experiments, a single-cylinder, naturally-aspired, air-cooled, four-stroke diesel engine is used, and the test engine is loaded from 2.5 to 10 Nm with the gaps of 2.5 Nm at a constant engine speed of 1800 rpm.

2. Methodology

2.1 Experimental Stage

In the present research, a life cycle base environmental pollution cost analysis is investigated for a compression ignition engine fuelled by diesel, ethanol, and methanol fuels. In the tests, three fuel types are formed namely DF (completely diesel fuel), E10 (diesel fuel of 90% and ethanol of 10%), and M10 (diesel fuel of 90% and methanol of 10%). The experimental data is gathered when the engine run at a constant engine speed of 1800 rpm in which the stable-data flow is observed and when the engine oil temperature reaches to 60 °C ±1°C to ensure more fair condition according to the changing test fuels. During this constant speed, the engine is loaded from 2.5 to 10 Nm with gaps of 2.5 Nm. The experiments are repeated three times to increase both the repeatability and reliability of the results.

In the present research, the data gathered from the direct injection, air cooled, single-cylinder diesel engine. Its main specification is tabulated below.

Table 1. Some important engine specifications.

Model	Lombardini 15 LD 350
Maximum power	7.5 HP/3600 rpm
Maximum torque	16.6 N m/2400 rpm
Displacement	349 cm^3
Compression ratio	20.3/1
Bore × stroke	82 mm × 66 mm
Injection nozzle	0.22 × 4 holes × 160°
Nozzle opening pressure	207 bar

The experimental rig is schematically given in Figure 2.

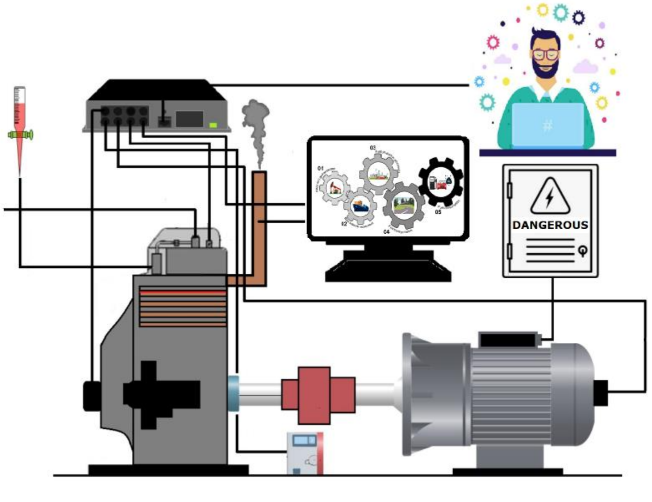

Fig 2. A schematic view of the experimental rig

Ethanol and methanol used in this study is purchased from MERCK, Germany (both>99.5% purity). Conventional diesel fuel is also supplied from a gas station in Düzce, Turkey. Then the conventional diesel fuel, ethanol, and methanol fuels are volumetrically blended to each other (See Step #1 in Figure 3).

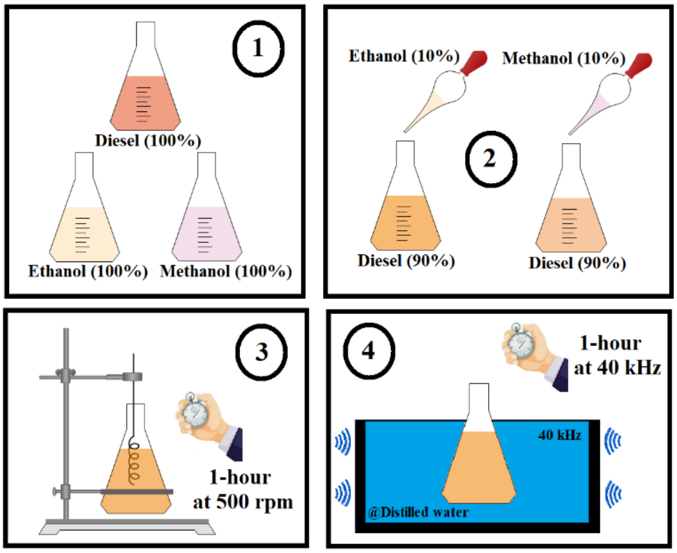

Fig. 3. Followed steps in the stable diesel-alcohol binary blends.

Firstly, to gather the reference data, the test engine run with completely diesel fuel. After that, diesel-ethanol (90% and 10% by volume) and diesel-methanol (90% and 10% by volume) binary blends are volumetrically mixture each other (See Step #2 in Figure 3). After the blending of two fuels into each other, a mechanic stirrer is used at 500 rpm during 1-hour (See Step #3 in Figure 3). After the stirring process, the fuel blend is exposed to ultrasonic waves at 40 kHz for 1-hour (See Step #4 in Figure 3). After these steps, the stable homogenous binary blends are achieved and ready for pouring into the fuel-tank. All steps to reach a stable fuel blends are schematically shown in Figure 3. Some main properties of the fuel samples are tabulated below.

Table 2. Properties of test fuel samples.

Properties	DF	E10	M10
Density (g/L)	833.4	828.1	828.4
Kinematic viscosity (mm^2/s)	2.4	2.2	2.2
Lower heating value (MJ/kg)	43.4	41.1	40.5
Oxygen content (wt.%)	0	3.4	4.8
Carbon content (wt.%)	86.5	83.4	82.1
Hydrogen content (wt.%)	13.5	13.2	13.1

2.2 Life cycle and pollution cost analysis

Life-cycle analysis is a systematic approach that analyzes the environmental impacts of products and services in detail. Developed by the Society of Environmental Toxicology and Chemistry [51]. It includes all stages from the extraction of a product's raw materials (from the nature) to its production, shipment, use, and finally disposal or recycling.

The environmental pollution cost analysis is related to the costing of environmental effect of the CO_2. This analysis unites the economic and environmental aspects together. The released CO_2 emission are transformed to economic aspects by utilizing the cost of CO_2. In this framework, the environmental costs are calculated using the following equation [47, 49, 50]. In this study, the cost of CO_2 is accepted to be C_{CO2}= 0.0327 $/kg [46].

The specific environmental pollution cost (SEP) is obtained in the following equation [47, 49, 50]:

$$SEP = C_{CO_2} e_{CO_2} \tag{1}$$

In the relevant equation, C_{CO2} refers to the cost of CO_2 emission and e_{CO2} represents the CO_2 emission released from the diesel engine used in this study.

During the lifespan of test engine, the CO_2 emission cost arising from the diesel engine is accepted as the total environmental pollution cost (TEP) and it can be found using the following equation [47, 49, 50]:

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

In the relevant equation, P represents the effective power (kW), N is the active running period per a year (h) and *t* is the total lifespan of the engine. Total lifespan of the engine, and the running period per a year are accepted to be 20 years, and 8000 h/year, respectively. On the other hand, the life cycle based total environmental pollution cost (TEP_{LC}) is related to the cost of CO2 emission arising from the engine and the pollution costs arising from the production of the the engine and fuel, as well. TEP_{LC} is determined as follows [47, 49, 50]:

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

Where m_{ICE} is the mass of the internal combustion engine used in the study, e_{ICE} shows the emission amount of the engine material, $\dot{Q}_f$ refers to the heat energy of fuel and e_f is the emission arising from the fuel production processes. The mass of the engine is equal to 33 kilograms. The emission amount of the engine material is accepted to be 3.012 kg-CO_2/kg [47, 49, 50]. The emission arising from the fuel production process is taken 0.0833 kg-CO_2/MJ for neat diesel fuel [52], 0.0971 kg-CO_2/MJ for the methanol [53], and 0.0248 kg-CO_2/MJ for the ethanol [54]. The emission arising from the fuel production process is calculated considering the mass fractions of alcohol and diesel blend as follows:

$$e_f = \frac{\dot{m}_D e_{F,D} + \dot{m}_{BD} e_{F,BD}}{\dot{m}_D + \dot{m}_{BD}} \tag{4}$$

The life cycle based specific environmental pollution cost (SEP_{LC}) is calculated using the Eq. (5) [47, 49, 50].

$$SEP_{LC} = \frac{TEP_{LC}}{(PNt)} \tag{5}$$

The overall CO_2 emission parameter (£) is obtained using the following equation [46]:

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

Where $\dot{m}_{CO_2}$ refers to the mass flow rate of CO_2 emission arising from the engine and $\dot{W}_{net}$ represents the net-work output rate of the engine.

The payback period of the engine (PP) is calculated using the Eq. (7) [55]:

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

In the equation (7), PEC refers to the purchased equipment cost, OM represents the cost of operation and maintenance, c_{el} and c_f shows the electricity, and fuel prices, respectively.

Then the environmental payback period (EPP) can be found using the Eq. (8) [46, 47, 49, 50]:

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

Finally, the life cycle based environmental payback period (EPP_{LC}) is calculated using the following equation [46, 47, 49, 50]:

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

The purchased equipment cost of test engine was PEC= 60000 \$. The unit cost of electricity and neat diesel fuel is taken to be c_{el} 0.1212 \$/kWh and c_f= 2.932x10-5 \$/kJ respectively [56]. The unit cost of biodiesel-diesel blends was c_f= 2.792x10-5 \$/kJ for TPO10D90, c_f= 2.507x10-5 \$/kJ for TPO30D70 and c_f= 2.218× 10-5 \$/kJ for TPO50D50. The maintenance and operation cost of the engine is taken to be 1.092% of purchased equipment cost [57].

The experimental steps and conditions followed in this study are as follows.

- Test fuels are prepared and characterized.
- The test engine is fuelled with a given test fuel. Then the engine is operated and waiting for that the oil temperature reached up to 60 ^{o}C.
- After that, the engine is loaded from 2.5 Nm to 10 Nm with the intervals of 2.5 Nm.
- During all experiments, the engine speed kept constant value of 1800 rpm.
- Injection pressure is kept as constant in all experiments to be 207 bar (catalog value).
- Measurements are started for each varying-parameters when the data flow is stable.

Each measurement is repeated three times in order to take the reliable, and repeatable experimental results. Then overall uncertainty of the experimental results is calculated with the following equation. In the calculation, since two measurement results – CO_2 emission a mass flow of fuel – are used, the overall uncertainty value is obtained, accordingly. CO_2 emission is recorded by the aid of K-Test brand exhaust gas analyzer. The relevant devise is able to self-calibrate and is capable of measuring the CO_2 emissions among 0-20% with an accuracy of 0.01%. On the other hand, the fuel-consumption is recorded from a precision scaled glass burette for a minute. The variation on fuel amount is read within ±1 mL per cent of volume. Accordingly, the uncertainty value arising from the CO_2 emission and fuel-consumption is calculated to be 0.75 % and 1%, respectively.

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \tag{10}$$

Where W_R is the overall uncertainty value of the experimental rig, and W_n is the uncertainty values of the independent variables. R and x_n show the dependent factor, and independent variables, respectively [41-43]. Accordingly, the overall uncertainty value of the experimental results is obtained to be 1.25%.

3. Result and Discussion

Basically, the results presented in this paper are derived from the CO_2 emissions released by the test engine in which it was manufactured and it was fueled. Therefore, it is of great importance to understand and discuss the CO_2 emission trends according to the varying test fuels as well as their properties and the operating conditions. Accordingly, Figure 4 clearly gives the variation of CO_2 emissions against the engine load for each test fuel. As it is known, conventional fuels (diesel and gasoline fuels) are normally composed entirely of hydrogen and carbon atoms. However, the fuel that reacts with the air taken into the cylinder for the combustion process to take place also forms other exhaust pollutants other than CO_2 and H_2O [58]. As can be seen from Figure 4, conventional diesel fuel caused the lowest CO_2 emissions for all engine loads. In other words, CO_2 emissions were increased with the addition of ethanol or methanol to the diesel fuel. The reason for this can be explained by the oxygen in the chemical composition of ethanol and methanol additives. Namely, there are no oxygen molecules in conventional diesel fuel [59-62]. Normally, conventional fuels only react with the oxygen in the air taken into the cylinder. That is when the test engine was fueled with DF fuel, the CO_2 observed was due to the oxygen in the air. With the presence of ethanol and methanol additives, hydrogen and carbon, as well as oxygen, were added to the binary fuel blend. This case further oxidized the carbon atoms in the fuel content. Therefore, CO_2 emissions for E10 and M10 test fuels are higher than that of DF test fuel. It is also seen from the figure that the CO_2 emission for all test fuels decreases step by step with the increment of engine load. Possibly, this case may be associated with the rise in the in-cylinder temperature value. The increase in the engine load, the improvement of the performance metrics, the increase in power while the piston frictions remain constant also may trigger the reduction of CO_2 emissions in lower engine loads.

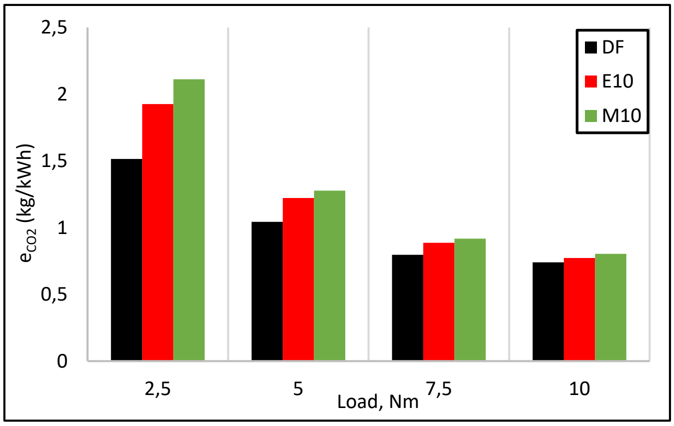

Figure 4. Variation of CO_2 emission with engine load.

In addition, it is seen that CO_2 emission is higher than that of E10 test fuel at a given engine load when the engine fuelled with M10 test fuel. The reason behind it can be attributable to higher oxygen content of pure methanol additives as can be seen in Table 2. Higher oxygen atoms react more carbon atoms and as a consequence of this phenomena, higher CO_2 emissions are recorded for M10 test fuel. Another reason is associated with the lower energy content of M10 additives in comparison with that of E10. In this case, more fuel mass is injected into the combustion chamber to be reached the same engine load when the engine runs with M10. This case also clearly explains why CO_2 emission is observed for the relevant test fuel at all engine loads. Accordingly, the increment in CO_2 emissions is totally 17.37% for E10 test fuel and 24.76% for M10 test fuel. Similar conclusions for the CO_2 trend were also reported by the previous works [63-72].

Figure 5 and 6 illustrate the total environmental pollution cost (TEP) and the life cycle based total environmental pollution cost (TEP_{LC}), respectively for each test fuel according to varying engine load. From the figures, the lowest TEP, and TEP_{LC} values at each engine load are noticed for DF test fuel. Then E10 and M10 test fuels respectively followed to DF test fuel in terms of TEP, and TEP_{LC}. The reason why the highest TEP and TEP_{LC} is obtained for M10 test fuel can be explained by the highest CO_2 emission as well as the highest fuel consumption of M10 test fuel at any engine load. As the engine load increases, total environmental pollution cost values for each test fuel reduces. This may be attributable to the improved fuel consumption and decreased CO_2 emissions at high engine loads. Accordingly, the lowest TEP values are 3736.2 \$, 4749.3, and 5208.1 and the lowest TEP_{LC} values are calculated to be 10335.9 \$, 10889.9 \$, 12117.1 \$ at 2.5 Nm, whilst the highest TEP values are calculated s to be 7308.7 \$, 7625.9 \$, and 7931 \$, and the highest TEP_{LC} values are calculated to be 18714.6 \$, 18835.6 \$, and 19284.1 \$ for DF, E10, and M10 test fuels at 10 Nm. Considering all engine loads together, the average TEP_{LC} is higher by 4.13% and 8.61% for E10 and M10 test fuels according to that of DF test fuel.

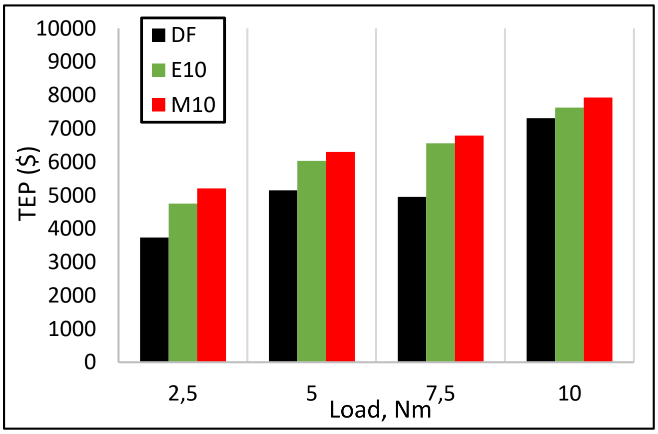

Fig. 5. Total environmental pollution cost

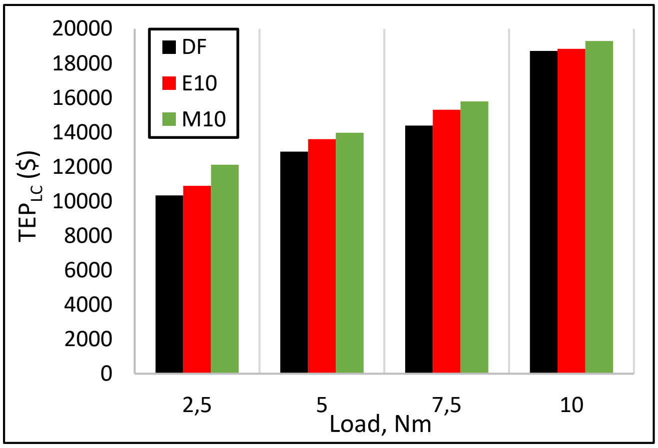

Fig. 6. Life cycle based total environmental pollution cost

Another parameter handled in this paper is environmental pollution cost and life cycle based environmental pollution cost parameters. Their variation according to the engine load is illustrated in Figure 7 and Figure 8, respectively. In constrast to TEP and TEP_{LC} values, the SEP and SEP_{LC} values are dropping as the engine load increases. However, the orders at any engine load is the similar to that of TEP_{LC}. That is the lowest SEP and SEP_{LC} values are always achieved for DF test fuel, and the highest ones are achieved for M10 test fuels. The highest SEP_{LC} values are calculated to be 0.1371 \$/kWh, 0.1444 \$/kWh, and 0.1607 \$/kWh for DF, E10, and M10 test fuels at 2.5 Nm. Given that all life cycle based specific environmental pollution cost together, SEP_{LC} are lower by 4.78% for E10 test fuel, and 11.2% for M10 test fuels, respectively.

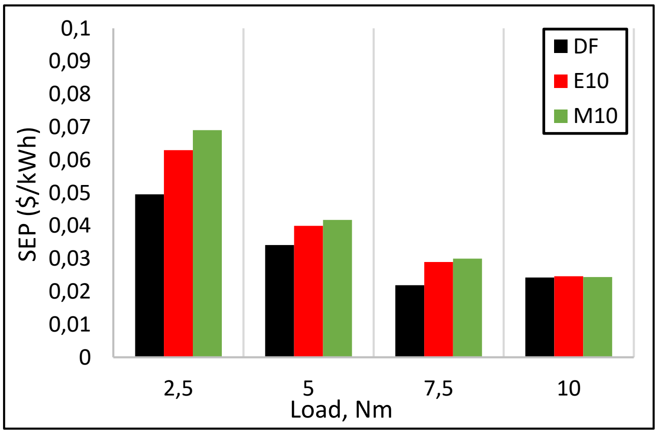

Fig. 7. Specific environmental pollution cost

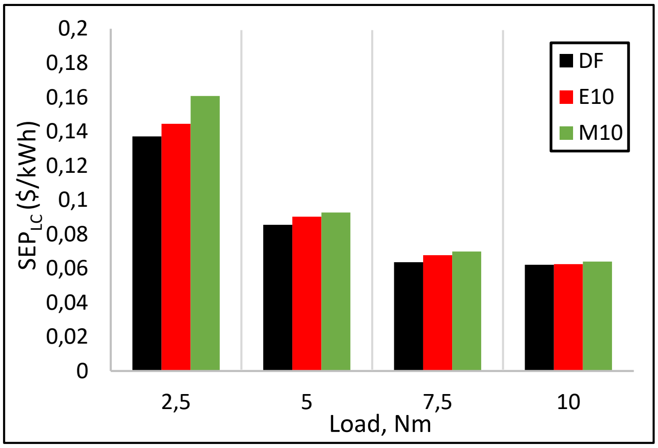

Fig. 8. Life cycle based specific environmental pollution cost

Figure 9 gives the total CO_2 emission parameter (£) according to varying engine load for each test fuel. As can be seen in Figure 9, the lowest £ values are obtained when the engine is fuelled with conventional DF at all engine load. On the other hand, the highest value is noticed at any engine load for M10 test fuel. As the engine load decreases, £ value gradually drops for each test fuel. The reason of this drop can be explained with the reduction of CO_2 emissions at higher engine loads (See Figure 4). Accordingly, the highest £ value is 4.21x10^{-4} kg/kJ for DF, 5.35x10^{-4} kg/kJ for E10, and 5.87x10^{-4} kg/kJ for M10 test fuel when the engine operates at 2.5 Nm. Overally, the £ value increases by 21.14% for E10 and 28.76% for M10 test fuels as compared to that of DF.

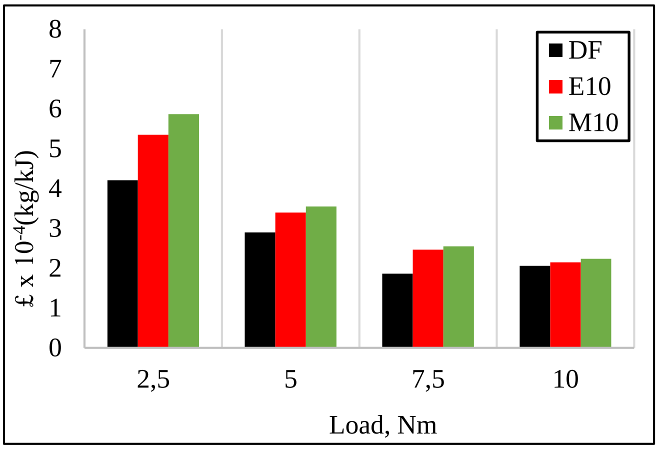

Fig. 9. Volume variation of the engine

Finally, the parameters considered in this study is the environmental payback period and life cycle based environmental payback period, which is given in Figures 10 and 11, respectively. As can be seen from the relevant figures, the conventional diesel fuel at any engine load has the less EPP and EPP_{LC} values. As the engine load increases, both EPP and EPP_{LC} run their minimun values.

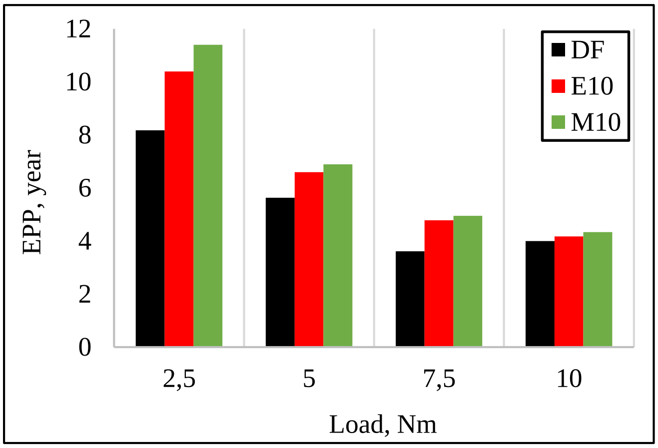

Fig. 10. Environmental payback period

Accordingly, the highest EPP_{LC} values are calculated to be 22.62 years for DF, 23.83 years for E10, and 26.52 years for M10 test fuels. The main reason behind the longer payback period for E10 and M10 test fuels according to that of conventional DF is associated with lower energy content of the alcohols (See Table 2). Since their energy content is lower, both environmental payback period and life cycle based environmental period gets longer. E10 and M10 test fuels have 4.78 and 11.2 times longer EPPLC than that of conventional. Similar results are also reported by the previous works [47, 50].

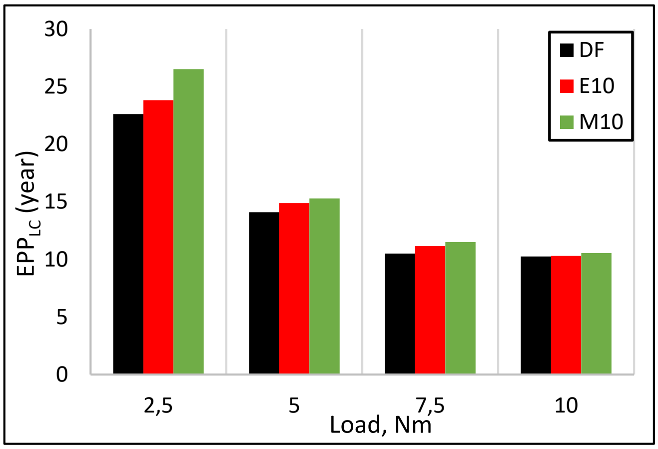

Fig. 11. Life cycle based environmental payback period

4. Conclusions

In the present paper, commonly used biofuels –methanol and ethanol – are separately blended into the conventional diesel fuel at the volumetric rate of 10%. The experiments are conducted at different engine loads changing from 2.5 to 10 Nm with the gaps of 2.5 Nm. During all experiments, the engine run at the crankshaft speed of 1800 rpm. Under these operating conditions, the life cycle based environmental pollution cost analyses are studied for methanol and ethanol-blended diesel fuels. In the conclusion, the following bullets can be briefly derived from this research.

- Thanks to high-oxygen content of methanol and ethanol additives, the level of CO_2 emissions emitted by the test engine highly increased. Given that all engine loads together, the increment in CO_2 emissions is cumulatively 17.37% for E10 test fuel and 24.76% for M10 test fuel.
- Lower energy content of the alcohols than that of conventional diesel fuel, the engine performance worsens.
- Conventioanal DF has 4.78-times shorter EPP_{LC} value than E10 test fuel and 11.2-times shorter EPP_{LC} value than M10 test fuels.
- The highest £ value is calculated to be 4.21×10^{-4} kg/kJ for conventional DF, whilst it is equal to 5.35×10^{-4} kg/kJ for E10 test fuel, and 5.87×10^{-4} kg/kJ for M10 test fuel at 2.5 Nm. As the engine load goes from 2.5 Nm to 10 Nm, £ value drops for each test fuel. Given that all £ values at all engine loads together, it is higher by 21.14% for E10 and 28.76% for M10 test fuels in comparison to that of DF.
- Total life cycle based environmental pollution values showed that DF is lower by 4.13% and 8.61% for E10 and M10 test fuels considering all engine loads together.

To sum up, conventional diesel fuel emits fewer CO_2 emissions and ensures fuel economy as compared to those of diesel-biofuel blends when the diesel engine is fed by completely diesel fuel. The reason behind these outputs was already reported by many researchers by referring to both the oxygen-free content and high calorific value of the diesel fuel. Given that the lifecycle-based analysis, diesel fuel still presents the promising results. Clearly, the reason behind it can be explained with the unit price, fewer CO_2 emitting in the production stages as well as the high energy density of conventional diesel fuel in comparison to those of ethanol and methanol biofuels. At this point, author suggests that future works may use some solid or liquid agents such as nanoparticles, quantum dots, and hydrogen gases along with the diesel-biofuel blends in order to enhance the engine performance and to pull back the increasing CO_2 emission levels. Additionally, this paper proves that any step to be taken by the decision-makers in the fuel processing stages will be very useful to the payback period of the fuels and contribute to the mitigation of total CO_2 emissions of the fuels' life cycle.

Nomenclature

C_{CO2}	cost of CO_2 emission (\$/kg)
c_{el}	electricity price (\$/kWh)
c_f	fuel price (\$/kWh)
e_{CO2}	CO_2 emission emitted by the engine (kg/kWh)
e_f	emission of fuel producing process ($kgCO_2$/MJ)
e_{ICE}	emission rate of material of engine (kCO_2/kg)
£	total CO_2 emission parameter (kg/kJ)
m_{ICE}	mass of internal combustion engine (kg)
$\dot{m}$	mass flow rate (kg/s)
P	effective power (kW)
Q_f	heat energy of the fuel (kJ/h)
t	total lifetime (year)
W_{net}	net work output rate (kW)

Abbreviations

CI	compression ignition
CO_2	carbon dioxide
DF	Diesel fuel
E10	Diesel (90%) + Ethanol (10%) blend
EPP	environmental payback period (year
EPP_{LC}	life cycle based environmental payback period (year)
OM	operation and maintenance cost (\$)
M10	Diesel (90%) + Methanol (10%) blend
PEC	purchased equipment cost (\$)
PP	payback period (year)
SEP	specific environmental pollution cost (\$/kWh)
SEP_{LC}	life cycle based specific environmental pollution cost (\$/kWh)
TEP	total environmental pollution cost (\$/kWh)
TEP_{LC}	life cycle based total environmental pollution cost (\$/kWh)

Conflict of Interest Statement

The author declares that there is no conflict of interest in the present paper.

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