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Determination of Fuel Type for Optimal Performance and Emission in a CI Engine Used Biodiesel and its Blends via Multi-Criteria Decision Making

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Abstract

In this study, fuel type which provides optimum performance and emission in compression ignition (CI) engine used alternative fuel was determined by COPRAS (Complex Proportional Assessment) in multi-criteria decision making (MCDM), and it was ranked from good to bad. Furthermore, the engine performance and emission consequences obtained from the use of fuels are discussed. In the experiments, pure biodiesel, diesel, and biodiesel/diesel blend fuels at a ratio of 5, 20 and 50% by volume were used as an alternative fuel. The performance and exhaust emission characteristics of the engine have been obtained in the tests performed at 7.2 kW power output and 1500 rpm of the constant engine speed. According to experimental results, with the uptrend of the biodiesel ratio in the blended fuel, it has been observed that while the specific fuel consumption (SFC) is enhanced to diesel, the thermal efficiency (η) is partially reduced. At the same time, the emissions of the nitrogen oxide (NO_x), carbon monoxide (CO) hydrocarbon (HC), and carbon monoxide (CO) decreased while the carbon dioxide (CO_2) emission enhanced. According to the COPRAS method, the ranking of fuels from best to worst was calculated as B5>B20>B50>B0>B100.

Keywords: Biodiesel, Optimum performance and emission, MCDM, COPRAS

1. INTRODUCTION

Nowadays, while the energy needs of the developed countries increase, the negative impacts on the environment in the production and use of this energy come into prominence. In our era, vehicles have a large usage area in industrial. World's primary energy demand is expected to increase by 0.9% per year by 2040 [1]. Researchers are developing alternative fuels to meet the increasing energy needs of human beings and to less harm the environment. Biodiesel is derived from animal fats and vegetable oils as an alternative fuel, and it is used without any change in internal combustion engines. Biofuels obtained by chemical methods are environmentally friendly and renewable liquid fuel.

In the literature research, it was seen that the researchers made motor tests by using biodiesel fuels obtained from vegetable and animal fats.

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They evaluated the fuels used in respect of performance and exhaust emissions. When the performance and emission criteria are taken into account, the tested fuels give positive results in some of the evaluation criteria, and some of them have negative results. There is a very limited number of studies to determine the optimum fuel in terms of both performance and emission results, taking into account all evaluation criteria. This study aims to determine the optimum fuel by taking into account all the criteria and by introducing a holistic model.

Some of the experimental study results in the literature are as follows. Imtenan et al. [2] used six different test fuels from diesel and peanut biodiesel fuel mixtures in a 4-cylinder, turbocharged diesel engine. In the study, biodiesel tests showed an increment in SFC after 1500 rpm. When the emission results were examined, CO, CO_2, and HC emissions decreased, except for the amount of NO_x. The reason for the increment in NO_x was interpreted as the healing of combustion because of oxygen (O_2) in the biodiesel and the increase in temperature inside the cylinder. Labeckas and Slavinskas et al. [3] examined the emissions of direct injection and four-cylinder CI engine fueled on pure methyl ester of the rapeseed and its 5, 10, 20 and 35% blend with standard diesel. They stated that CO and HC emissions had reduced whereas NO_x emissions augmented for biodiesel according to diesel. Desantes et al. [4] tested the rapeseed oil biodiesel and diesel fuel mixture in a single cylinder CI engine. They reported that the smoke emissions, NO_x and CO remarkably decreased. In another study [5], it was stated that the SFC increased because of the low latent heat value of palm oil biodiesel. Jeong et al. [6] used methyl ester of the rapeseed and its mixture as a fuel in a CI engine. They expressed that because of the density and low thermal value of biodiesel, SFC increased according to diesel.

Some studies conducted with multi-criteria decision making (MCDM) methods in the energy sector are as follows. Nwokoagbara et al. [7] used AHP and TOPSIS methods from MCDM to determine the best micro algae type for biodiesel production. Durairaj et al. [8], fuzzy AHP and GRA-TOPSIS methods were used to select the most suitable fuel for biodiesel fuels produced from mahua, cotton, flax, neem, jatropha, meusaferra and pongamia seeds. In another study, it has evaluated biodiesel origin vegetable and animal, and their mixtures with diesel by using MULTIMOORA method in respect of motor performance, combustion and emission characteristics [9]. Yazdani-Chamzini et al. [10] used the COPRAS method to choose the best renewable energy source from wind power, hydroelectric, solar-thermoelectric, biomass, and biofuel. Considering the studies in other areas, Chatterjee and Chakraborty operated the COPRAS method to select the best material [11].

In this study, the impacts of different fuels on the performance and emission characteristics of the engine were empirically investigated. In addition, the fuel type which provides the optimum result for these parameters is determined by COPRAS method. The different results of the experimental results are only possible if the operating and structural conditions of the engine change. In this study, no changes were made to the engine, only fuels with different physical and chemical properties were used.

2. MATERIAL AND METHODS

This section provides information about the equipment and materials used in the experimental study. The theory of the proposed multi-criteria decision-making method is also described.

2.1. Testing Procedure and Method

The tests were performed under constant engine load (7.2 kW). A load bank with resistance connected to the alternator consumes the generated electricity, and the diesel engine is loaded. The engine tests were carried out in a set of diesel generators given in Figure 1.

A technical specification for the alternator and the CI engine are presented in Table 1. A diesel engine with four cylinders, direct-injection, naturally aspirated and water-cooled continuously works at 1500 rpm of the constant speed.

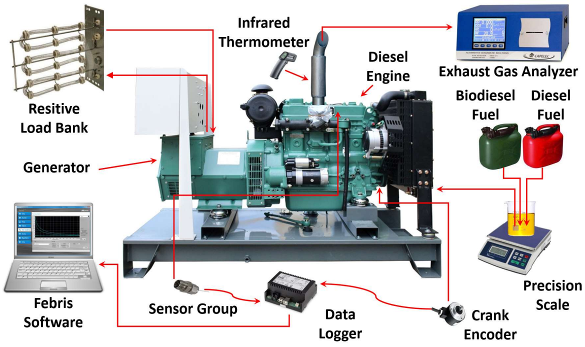

Figure 1. The test setup

Table 1. The specifications for the alternator and diesel engine

Diesel Engine	
Brand - Model	Fawde - 4DW81-23D
Maximum power output	18 kW
Engine speed	1500 rpm
Number of cylinders	4
Compression rate	17:1
Compression system	Direct injection
Number of injectors	4
Injector pressure	400 bar
Injection time	23 °CA bTDC
Cooling system	Water cooled
Cylinder diameter x stroke	85 x 100 mm
Total cylinder volume	2400 cm^3
Alternator	
Model	NWR 22
Standby power	17.5 kW
Phase - Frequency	3 PH - 50 Hz
Power factor	0.8

In order to determine exhaust gas emissions during the use of fuels, the Capelec CAP 3200 exhaust emission measurement device was utilized. In order to gauge the amount of fuel consumed per unit time, a digital scale with 6 kg capacity and 1 gram precision, and a digital stopwatch were used. Raytek Rayngerr ST4 infrared thermometer with 1 °C sensitivity was preferred to measure the exhaust manifold temperature.

2.2. The Methodology

In this study, COPRAS method has been used in MCDM methods. The criteria have consisted of the engine performance and emission indicators. The ranking degree of the alternatives has determined by being evaluated these criteria. The elements used in this model are described below.

2.2.1. Test fuels

Biodiesel obtained from the mixture of safflower oil and canola was used in the experiments. The diesel fuel was mixed with 5, 20 and 50% by volume of pure biodiesel fuel and five different fuel with different properties was prepared. The mixtures are designated B5, B20, and B50. The diesel fuel is called B0, and the pure biodiesel is named as B100. The physical and chemical specifications of fuels were measured at TUBITAK Marmara Research Center and presented in Table 2.

Table 2. The physical and chemical properties of the fuels

Properties	**Diesel (B0)**	**Biodiesel (B100)**
Density (kg/m^3)	840	883.9
Kinematic viscosity (mm^2/s)	2.800	4.010
Calorific Value (kJ/kg)	43300	38600
Cetane number	52	52,6
Flash point (°C)	78	188
Iodine number (gI/100g)	~0	116
Water content (mg/kg)	~0	202

2.2.2. Evaluation Criteria

The criteria for the proposed model were determined as the specific fuel consumption (SFC), thermal efficiency (η), exhaust manifold temperature (EMT), NO_x, CO_2, CO, and HC.

The SFC is the proportion of the consumed fuel quantity per unit of time to the power output [12]. The SFC calculated with Eq. (1).

$$SFC = \frac{Fuel\ Consumption}{VxI} x3600 \tag{1}$$

where I is electric current (A) and V is a voltage (V). The specific energy consumption (SEC) is an important parameter in comparison of fuels with different calorific values (CV). It is the quantity of energy consumed by an engine versus each unit of power output. It is calculated with Eq. (2) [13].

$$SEC = SFCxCV \tag{2}$$

where calorific value (kJ/kg) and SFC (kg/kWh).

The thermal efficiency (η) is designated as the proportion of energy taken from the engine to the energy consumed and is calculated with Eq. (3).

$$\eta = \frac{3.6x10^6}{SFCxCV} \quad (3)$$

The exhaust manifold temperature (EMT) is an important parameter because it is an indicator of the combustion temperatures of the fuels in the tests. The temperature of the exhaust manifold was measured by an infrared thermometer.

The NO_x emission is an evaluation criterion. The nitrogen atoms inside the air turn into NO_x, which is among the exhaust emissions under the high temperatures during the combustion [14]. The CO_2 emission occurs at the end of the chemical reaction within the cylinder in which carbon atoms transform to CO_2. If combustion does not materialize completely, they are discharged from the exhaust as CO. The HC emission represents the fuel that is partially oxidized or not oxidized due to the less of the O_2 in the intake air [15].

2.2.3. COPRAS Method

The COPRAS (Complex Proportional Assessment) method was improved by Zavadskas and Kaklauskas in 1996 [16]. It is a very convenient method for ordering and evaluating decision options considering the maximization and minimization of the criteria [17]. The process steps of the COPRAS method are described as follows [18].

The decision matrix consisting of data on alternatives and criteria is created as Eq. (4).

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (4)$$

where i is alternatives ($i = 1, 2, 3, \ldots, m$), and j is criteria ($i = 1, 2, 3, \ldots, n$).

By taking into account the weight of the criteria (q_j), the decision matrix is normalized by applying Eq. (5).

$$d_{ij} = \frac{x_{ij}\, q_j}{\sum_{i=1}^{m} x_{ij}} \quad (5)$$

The weighted normalized indexes are added by Eq. (6).

$$S_{+i} = \sum_{j=1}^{n} d_{+ij}\,;\; S_{-i} = \sum_{j=1}^{n} d_{-ij} \quad (6)$$

The relative importance of the alternatives is calculated by Eq. (7).

$$Q_i = S_{+i} + \frac{S_{-min}\sum_{i=1}^{m} S_{-i}}{S_{-i}\sum_{i=1}^{m}\frac{S_{-min}}{S_{-i}}} \quad (7)$$

Q_i is sorted in descending order. The higher Q_i is the greater relative importance. The benefit degree of alternatives is determined through Eq. (8).

$$N_i = \left(\frac{Q_i}{Q_{max}}\right) 100\% \quad (8)$$

The alternative with 100 degrees of benefit is the best option. The others are ranked in descending order.

3. RESULTS

3.1. Performance Results

The SFC and SEC were calculated according to the measurement results. That values of the biodiesel and their blends are given in Figure 2.

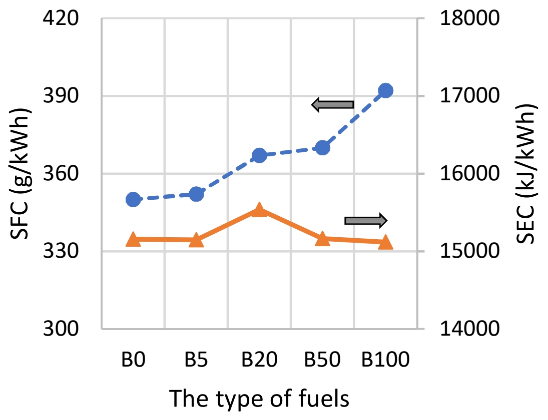

Figure 2. The variations of the SFC and SEC

The main reason for the high SFC of biodiesel and its blends compared to diesel is that the calorific value of biodiesel is lower than diesel. In order to generate the same amount of energy as diesel, a larger amount of biodiesel fuel must be consumed massively. In addition, the quantity of fuel injected into the cylinder in biodiesel and its mixtures is higher than standard diesel, because the density of biodiesel fuel is higher than standard diesel fuel. SEC is a very important parameter used in the comparison of fuels produced from different raw materials. It is seen that the maximum SEC in the B20 fuel is realized.

Figure 3 shows the thermal efficiency of biodiesel and its blends.

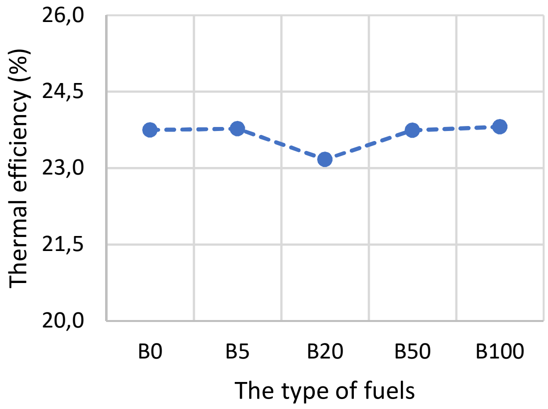

Figure 3. The variations of the thermal efficiency

When the graph is examined, the TE of all fuels is very close to each other. The thermal efficiency of the B20 fuel is slightly lower than the others. Inasmuch as the SEC of the B20 is more than others.

The exhaust manifold temperature (EMT) of biodiesel and their blends are given in Figure 4. The EMT is an important parameter because it is an indicator of the combustion temperatures of the fuels. The combustion within the cylinder improved through the addition of biodiesel to diesel fuel.

There was no regular reduction according to biodiesel rate because the C/H ratio of the fuel mixture and the oxygen content in it are differentiated. Therefore, combustion characteristics can be seen differently. Considering that the SEC of the B20 fuel is higher than the other biodiesel blends, it is normal to be high the EMT of the B20 fuel. It is thought that the temperature of the exhaust gases is increased for B20 due to the extension of the combustion to the expansion period.

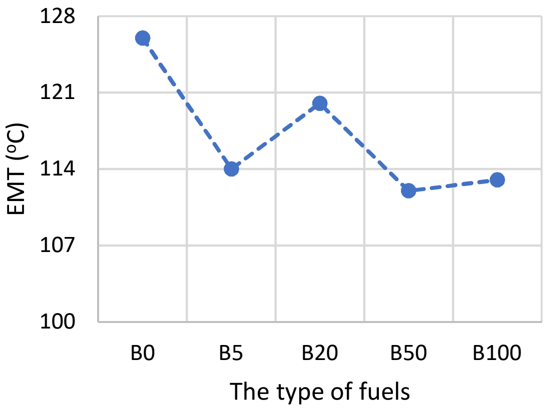

Figure 4. The variations of the EMT

3.2. Emission Results

The CO emission, which is one of the main parameters of exhaust emission, exists the combustion products when the air-fuel ratio is low. If the physical and chemical properties of the fuels, engine load, and spray characteristics change, the amount of CO formation changes. When there is enough O_2 in the burning chamber, the CO changes during combustion and turns into CO_2. The CO emissions and CO_2 emissions of biodiesel and their blends are given in Figure 5.

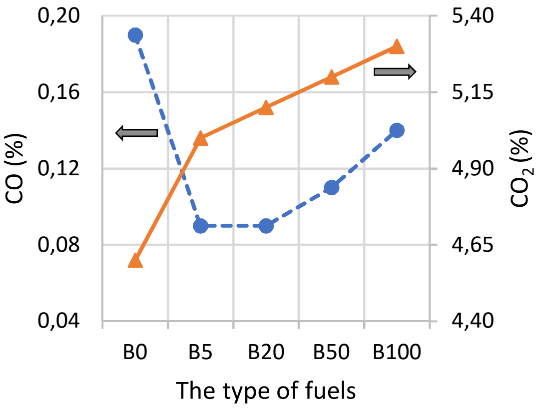

Figure 5. The variations of the CO and CO_2 emissions

The CO emission indicates the lost chemical energy that cannot be used in the engine. B5 and B20 fuels improve combustion and reduce CO emissions. It also increases CO_2 emissions. The positive effect of oxygen in biodiesel decreases due to the increase in SFC and the decrease in the air-fuel ratio for B50 and B100 fuels.

Figure 6 shows the NO_x and HC emissions of biodiesel and its blends.

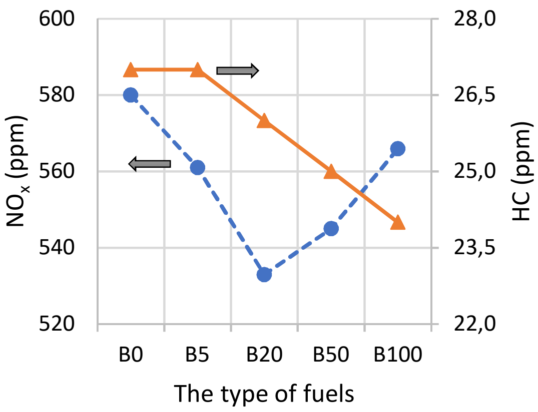

Figure 6. The variations of the HC and NO_x emissions

The main reason for the entity of HC emissions in combustion products is that the fuel starts to burn before the ignition temperature is reached or the oxygen in the environment is insufficient. When the biodiesel rate in the fuel mixtures increases, HC emissions are observed the decrease. The lowest HC emission was viewed in B100.

When the internal temperature within the cylinder rises, NO_x is generated by the reaction of nitrogen in the air with oxygen. Because of the use of biodiesel produced from different raw materials, it has been noticed that NO_x emissions exhibit very different behaviors in the literature research. The lowest NO_x emission was observed in B20 fuel. The TE of B20 fuel is low compared with other fuels. It is estimated that the in-cylinder temperature of the B20 fuel is lower than other fuels.

3.3. Computations of the COPRAS

According to the experimental results, the evaluation criteria for the selection of the fuel that gives the best performance and emission results are determined. These criteria are SFC, TE, EMT, NO_x, CO_2, CO, and HC. The maximization oriented criteria are TE and EMT, while the other criteria are the minimization oriented. The weights of the criteria were calculated using the simple scoring technique, a popular multi-criteria decision method. The most important value was 9 points and the lowest value was chosen as 1. The authors assigned a score of 1-9 to the criteria. Then each criterion was divided into total points and the weights of criteria were calculated as a percentage. The values assigned to the criteria are SFC: 8 points, TE: 9 points, EMT: 2 points, NO_x: 6 points, CO_2: 4 points, CO: 2 points, and HC: 2 points. Multi-criteria decision-making methods such as AHP, SWARA, and ENTROPI may be preferred to determine the weights of the criteria. The weights of the criteria (q_i) and the initial data of the alternatives are given in Table 3.

Table 3. The decision matrix

	SFC	**TE**	**EMT**	**NO_x**	**CO_2**	**CO**	**HC**
B0	350	23.75	126	580	4.6	0.19	27
B5	352	23.77	114	561	5.0	0.09	27
B20	367	23.17	120	533	5.1	0.09	26
B50	370	23.74	112	545	5.2	0.11	25
B100	392	23.81	113	566	5.3	0.14	24
q_i	24%	27%	6%	19%	12%	6%	6%
	Min.	Max.	Max.	Min.	Min.	Min.	Min.

The decision matrix was normalized and weighted using Eq. (5). It is given in Table 4.

Table 4. The normalized and weighted matrix

	SFC	**TE**	**EMT**	**NO_x**	**CO_2**	**CO**	**HC**
B0	0.0459	0.0542	0.0129	0.0396	0.0219	0.0184	0.0126
B5	0.0461	0.0543	0.0117	0.0383	0.0238	0.0087	0.0126
B20	0.0481	0.0529	0.0123	0.0364	0.0243	0.0087	0.0121
B50	0.0485	0.0542	0.0115	0.0372	0.0248	0.0106	0.0116
B100	0.0514	0.0544	0.0116	0.0386	0.0252	0.0135	0.0112

The relative importance (Q_i) of alternatives was calculated by Eq. (7). In addition, Eq. (8) was used to determine the benefit degree (N_i) of decision alternatives. S_{+i}, S_{-i}, Q_i, N_i, and the ranking of the fuels are given in the Table 5. According to this order, it is seen that B5 fuel is the first order and B100 fuel is the last order.

Table 5. The ranking of the fuels

	S_{+i}	S_{-i}	Q_i	N_i	Rank
B0	0.0672	0.1383	0.3925	94.9%	**4**
B5	0.0660	0.1295	0.4134	100.0%	**1**
B20	0.0652	0.1296	0.4125	99.8%	**2**
B50	0.0657	0.1327	0.4047	97.9%	**3**
B100	0.0660	0.1399	0.3875	93.7%	**5**

4. CONCLUSION

There are numerous studies on the use of biodiesel in the literature. However, few studies have been found in which the results of engine performance and emission tests are optimized with a holistic approach. The most difficult subject as an interpretation of the experimental results is the decision making according to many parameters. In this study, both the experimental results were interpreted separately, and the results were optimized by a multi-criteria decision-making method.

The tests were carried out in a diesel engine operating at 7.2 kW load and at a constant engine speed of 1500 rpm. The pure biodiesel fuel is mixed with 5%, 20% and 50% diesel fuel and named as B5, B20, and B50. The diesel fuel and pure biodiesel fuel are called B0 and B100 respectively. In the tests, SFC, SEC, EMT and TE of the fuels were determined. CO, CO_2, NO_x and HC emissions were also measured.

According to the performance parameters, it has been observed that fuel consumption increases as the biodiesel rate increases within blend fuel. The TE of fuels are close to each other, and EMT has also decreased. In the tests, CO, HC, and NO_x emissions were lower in the fuel mixes with biodiesel and CO_2 emissions increased compared to diesel fuel.

In the optimization study conducted with COPRAS, one of the multi-criteria decision-making methods, fuels are rated according to performance and emission characteristics. Consequently, the best performance emission results in this diesel engine were obtained in B5 fuel. According to the COPRAS optimization method, fuel ranking is B5>B20>B50>B0>B100.

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