Advances in Environmental Technology 3 (2020) 149-159

Advances in Environmental Technology

journal homepage: http://aet.irost.ir

Investigation of emissions and performance of diesel engine with the blend of Jatropha Diesterol Fuel using response surface methodology

Navab Kazemi*[1], Seyed Mohammad Safieddin Ardebili[2], Niloofar Alizadehbehbahani[1]

[1]Department of Agricultural Machinery and Mechanization, Faculty of Agricultural Engineering and Rural Developmet, Agricultural Sciences and Natural Resources University of Khuzestan, Ahvaz, Iran.

[2]Department of Biosystems Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.

ARTICLE INFO

Article history:
Received 29 January 2021
Received in revised form
11 April 2021
Accepted 11 May 2021

Keywords:
Biodiesel-ethanol-diesel
Emission
Performance
Jatropha
Response surface method

ABSTRACT

In this research work, the performance and the exhaust emissions of a CI engine operating on diesel-biodiesel-ethanol blended fuels were investigated. The main purpose of this study aimed to reduce the various emissions produced by the new blended fuels. The conventional transesterification reaction was carried out to produce biodiesel from Jatropha seeds. A one-cylinder, four-stroke CI engine was powered by green blended fuels at various engine speeds. Response surface methodology (RSM) was exploited to analyze the performance and exhaust emission parameters of a diesel engine in terms of fuel blends and engine speed. According to the results obtained, an engine speed of 2657 rpm, a biodiesel concentration of 10.26%, and an ethanol ratio of 2.21% were found to be the optimal values. The obtained experimental results showed that adding ethanol-biodiesel to pure diesel fuel increased the diesel engine's performance, including power and torque output. The results also showed that the CO_2 emission increased 9.6 % while CO, NO_X, and HC emissions in the biodiesel-ethanol-diesel fuel decreased 1.33%, 5%, and 26.1 %, respectively, compared to pure diesel fuel. The specific fuel consumption of the new blended fuel decreased by 6.9 % compared to pure diesel fuel.

1. Introduction

Air pollution is one the most important problems facing industrialized societies [1,2]. Also, the world's main energy resources are fossil fuels, which are being depleted, have high pollutant emissions, and increasing costs. For these reasons, mankind has begun to search for renewable energy resources [3-5]. Biofuel is an energy resource in the form of gas, liquid, or solid materials taken from biological resources[6-8]. The most important biofuels used in transportations are biodiesel and bioethanol [9]. Vegetable oils are the main sources for biodiesel production [10,11]. Biodiesel has high production costs, which is more than diesel fuel extracted from crude oil. Therefore, it is necessary to find methods for reducing the costs of biodiesel production and discover new sources. For instance, many non-edible plants can be used as suitable source materials, and Jatropha is one of them. The Jatropha plant, with the scientific name Jatropha Curcas L (J.C.), is found in many tropical and semitropical countries of Asia and Africa; recently, it has been brought to Iran [9,12]. Jatropha has rather big seeds that are shaped like a rugby ball. It contains 400-425 fruits, 1580-1600 seeds per kilo, and grows up to 6 m in height [13,14]. Considering population growth and undernourishment problems, especially in many African countries, scientists believe that it is better to produce biofuels from non-edible plants [15]. One of the most important characteristics of the Jatropha plant is that it can be planted anywhere, even in land not suitable for agriculture [16]. Another property of this plant is that it can be irrigated with agricultural wastewater and recycled water [17]. The three significant methods developed for the production of biodiesel from vegetable oil are pyrolysis, microemulsion, and transesterification [18]. Transesterification is the most common and more economical method for the production of biodiesel [19]. The

*Corresponding author.
Email address: navab20@yahoo.com
DOI: 10.22104/AET.2021.4675.1277

obtained biodiesel can be used directly in engines without any modification. Thus, biodiesel is a general term for a broad range of fuels containing oxygen with an ester basis. In other words, biodiesel is a fatty acid monoalkyl ester with long-chain molecules which is obtained from plants oil [14,20,21,22]. Various studies have proven that biodiesel can be used in conventional diesel engines for long operation times [23]. Researchers in many states, such as Missouri and Idaho, have applied different blends of biodiesels for use in city buses, heavy trucks, and tractors. The fuel blends are combinations of biodiesel percentages from 2.98% of B2, 20.80% of B20, and 100% of B100. Biodiesels usually consist of B20 (20% biodiesel and 80% diesel). Using pure biodiesel (B100) reduces 90% of toxic gas emissions, and B20 reduces 20-40% of these gases [24]. It is claimed that using a blend of biodiesel and diesel can reduce the danger of serious illnesses and health problems [25]. Diesel is not a suitable engine fuel for cold climates; in low temperatures, its viscosity increases, and engines will not start without additional accessories (biodiesel also has the same problem in cold conditions) [26]. On the other hand, ethanol has a very low freezing point, and it can improve diesel properties when added in low percentages [27]. The main problem with ethanol is that it is not dissoluble in diesel and forms an emulsion when blended with it, and needs to be stirred continuously [28]. However, ethanol can be dissolved in biodiesel with any percentage [29]. In fact, biodiesel acts as a distributor of ethanol inside diesel and forms a stable solution [30]. Ethanol is the second member of the aliphatic alcohols, which is taken from plant sugars and has similar properties to gasoline [31]. Ethanol is used in gasoline engines as a blended fuel with gasoline; however, it can also be used purely. Today, ethanol can be a reliable substitute for conventional fuels. Ninety-eight percent of the ethanol produced in the world is obtained by the fermentation of sugars [28]. The required sugar for ethanol production can be extracted from various sources such as starchy, sweet, or agricultural materials; industrial wastes; and Lignocellulosic constituents [32]. Mixtures of ethanol with up to 20% volumetric contents can be easily used with diesel and biodiesel in internal combustion engines without any basic modification [29]. Fuel blended with ethanol, diesel, and biodiesel is also called Diesterol [33,34]. A comparative analysis has been performed among fuel blends of Jatropha biodiesel (BJ50), Karanja biodiesel (BK50) and diesel (D100) in a single-cylinder, four-stroke, and water-cooled engines. The results of the analysis of emission at an 80% engine working load showed that Jatropha NOx was less than Karanja and pure diesel [35]. From another perspective, Lapuerta et al. (2008) reported that diesel and biodiesel have the same NOx emissions [36] In a study, Wu et al. (2009) have tested five typical biodiesel emissions in a turbocharged truck (ISBe6) and concluded that various biodiesels reduce particles emission from 53% up to 69% with respect to pure diesel [37]. Dorado et al. (2003) observed that NO_X emission is reduced by 20% for olive oil biodiesel [38]. In a different study, a volumetric Nitrogen Dioxides emission study was conducted for three kinds of biodiesel derived from Jatropha, sesame, and Honge (a kind of plant) and reported emissions of 970, 1000, and 900 ppm, respectively, in comparison with 1080 ppm for diesel fuel at an 80% working load [39]. Although a number of studies emphasize that the application of biodiesel/bioethanol in diesel fuel could lead to a cleaner environment by reducing engine-out emissions, the optimum concentration of the above-mentioned fuel blend is still a challenge. Therefore, this study aimed at suggesting the optimal ratio of biodiesel and ethanol in the fuel blend.

2. Materials and methods

In this study, Jatropha oil was provided from India. The Jatropha oil fatty acid profile was used to calculate molar mass. It had no impurity, so no processing was required. In the present work, Jatropha biodiesel was produced from Jatropha oil; 900g of molar mass, 1% potassium hydroxide as an alkali catalyst, and methanol with a molar ratio of 1: 6 were applied in this reaction. The biodiesel production reaction time was 1 h with stirring at 60̊C. Figure 1 presents the schematic of the biodiesel production procedure.

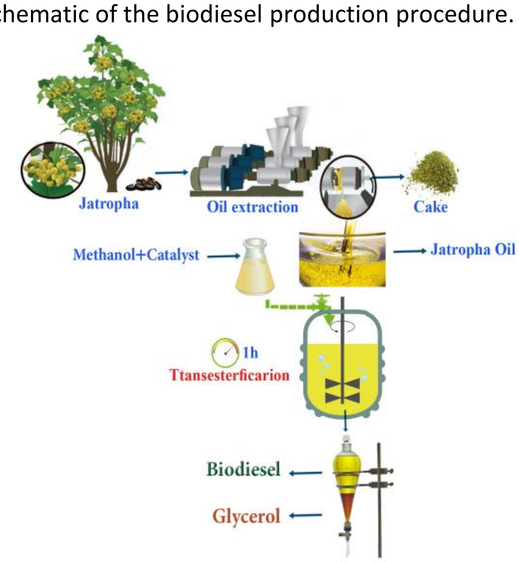


Fig.1. Schematic of biodiesel production procedure.

Following EN 14103, the gas chromatography analysis was performed in a GC Perkin Elmer Clarus 580 equipped with a flame ionization detector (FID) detector operating at 300°C and a capillary. The carrier gas was helium (purity 99.999) and the split flow was 50 mL/min. The column was a BPX–BIOD5 column (12 m*0.32 mm+2m*0.1). The temperature started at 60˚C and was kept for 2 min; then, it was increased to 210˚C on a 10˚C/min slope, and then to 230˚C on a 5˚C/min slope. It remained at this temperature for 10 minutes [19]. The methyl ester content was measured as 76.54%, which reached more than 96% by the washing process. Figure 2 shows the chromatography test results for Jatropha biodiesel.

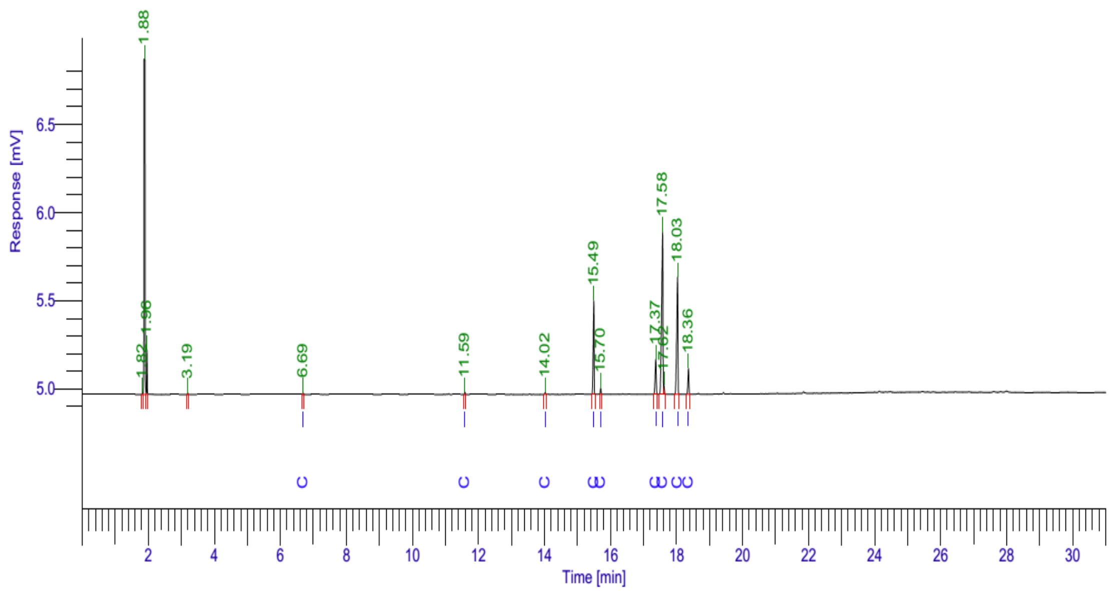


Fig. 2. Jatropha biodiesel fatty acids profile by GC analysis.

The produced biodiesel was tested for viscosity and density by an SVM-3000 model tester unit made by the Anton Paar Co., Austria. The viscosity and density of the biodiesel was measured at 40°C according to ASTM D4052 and ASTM D445 standards, respectively. The results for the properties of the Jatropha biodiesel in comparison with the diesel extracted from oil are presented in Table 1.

Table 1. Characteristics of Jatropha biodiesel.

Property	Method	Jatropha Biodiesel
Density (g/cm3)	ASTM D88	0.872
Flash point (°C)	ASTM D93	154
Ester content (%w/w)	EN 14103	>96

The fuel blends consisted of ethanol, Jatropha biodiesel, and diesel. After pretests and examining the different combinations for the continuous operation of the engine under a load, a diesterol fuel was selected as the reference with the following criteria: 3% ethanol; B0, B10, and B20 biodiesels with percentages of 0, 10, and 20, respectively; and pure diesel (E0B0D100). Fuel blends of ethanol, Jatropha biodiesel, and diesel were tested in a Lombardini single-cylinder, air cooled diesel engine located in the Renewable Energy Institute at the Tarbiat Modares University. The technical specifications of the engine are presented in Table 2. Tests were conducted at full load and rotating speeds of 1600, 2150, and 2700 rpm to measure the performance parameters of the engine and exhaust emissions. A 70 KW Eddy Current Dynamometer, model WE400, made by Mobtakeran Pars Andish (MPA) was used for measuring the torques, engine speeds, and power of the engine. In the present research, a gas analyzer setup model MDS 418 made by AVL Co., Austria, was used for measuring the engine exhaust emissions of CO, CO_2, HC, O_2, and NO_X. The real central control unit system of the dynamometer used for measuring the engine parameters is shown in Figure 3.

Table 2. Technical characteristics of the test engine.

Model	3LD 510
Manufacturing factory	Lambardini Company of Italy
Number of cylinders	1
Cylinder stroke	90 ml
Cylinder Diameter	85ml
Cylinder volume	510 cm^3
Maximum power (3000rpm)	12/2 hp (9KW)
Maximum torque (1800rpm)	33 Nm
Compression ratio	17/5: 1

Fig.3. Engine test set-up and test instruments.

3. Results and discussion

3.1. Engine-out emissions

3.1.1. NO_X emission

The results of the RSM analysis of NO_X reached a meaningful level of 5%, which showed the effect of biodiesel, ethanol, and engine rotational speed on nitrogen dioxide emissions. The coded factors for NOx are presented in Eq. (1):

$$NO_X = 151.81 - 62.06X_1 + 43.2X_2 + 10.36X_3 - 18.44X_1X_2 + 14.76X_1X_3 + 103.51X_1^2 + 8.8X_2^2 \quad (1)$$

The NOx response level to biodiesel and engine rotational speed variations are shown in Figure 4a. At different engine speeds with increasing of the biodiesel ratio in the fuel blend, the NOx was reduced and then increased. Twenty-nine percent of researchers have concluded that biodiesel reduces NOx emissions [۲٤].When the engine works in a condition closer to stoichiometric, the flame temperature rises, and NOx emission increases. 65.2% of researchers have concluded that in full load condition, using pure biodiesels increases nitrogen dioxides emissions for B100. Lin et al. (2009) studied vegetable oil methyl ester of eight types in biodiesels and observed that NOx emissions increased from 5.58% up to 25.97% in comparison to pure diesel [40]. In another study, Jatropha biodiesel blends of B100, B20, and B10 were investigated in a single-cylinder, four-stroke, water-cooled engine. The emissions were studied with respect to the average effective brake torque. NOx emission increased by adding average effective brake torque, but the NOx emission of pure diesel was lower than the biodiesel blends [41]. The fuel consumption increased by increasing the engine load, similar to the respective air amount in the cylinder. NOx emission is a function of combustion temperature. A higher combustion temperature produces more NOx. Since biodiesel oxygen content is higher than pure diesel, the combustion temperature is higher too [42]. On the other hand, by increasing the engine speed, the NOx increases in different biodiesel blends. Figure 4b shows the levels of NOx emissions with respect to biodiesel percentage variations in different engine speeds. The 2D graph of ethanol's effect on NOx emissions shows that by increasing ethanol ratio in the fuel blend, NOx also increases. This is caused by the oxygen content of ethanol, which results in both reactions with nitrogen and increasing combustion temperature that produce more NOx [26]. In one study, a four-cylinder direct injection engine (VGT) was tested using a diesel fuel blended with different ethanol fractions of 10% and 20% (E10, E20) [30]. The results showed that the amount of NOx depended on the engine's applied load. Thus, by adding engine load, the NOx emission increased [43].

3.1.2. Hydrocarbon (HC) emission

The results of the statistical analysis of HC reached a meaningful level at 5%. The HC response level graph with respect to biodiesel and engine rotational speed variations shows that by increasing biodiesel ratio in the fuel blend, hydrocarbon is reduced (Figure 5a). The final equation of the coded value is presented in Eq. 2.

$$HC = 14.54 - 3.55X_1 + 6.05X_2 - 0.077X_3 - 5.28X_1X_2 + 0.4X_1X_3 + 0.54X_2X_3 \quad (2)$$

The results of a study on a single-cylinder, four-stroke, air-cooled engine showed that with diesel-Jatropha biodiesel fuel, the HC was lower than pure diesel [13]. The higher cetane number of Jatropha biodiesel (50-52) relative to pure diesel (49) and the higher temperature of exhaust gases are the reasons for HC reduction in the Jatropha biodiesel fuel blends [44]. Wu et al. (2009) tested five typical biodiesels and reported that HC emission was reduced by 45% to 67% with respect to pure diesel [37]. In 80% of engine load, the HC emission of Karanja biodiesel was reduced with respect to Jatropha biodiesel and pure diesel. However, some researchers believe that due to the weak substructure and the low volatility of biodiesels, HC emissions increase [44]. Also, there is disagreement concerning carbon dioxide emission among researchers. Some of them claim that biodiesels increase carbon dioxide emission with respect to conventional diesel [45]. Studies have reported the reduction of carbon dioxide emission resulting from a lower ratio of carbon to hydrogen in biodiesels or both lower carbon content and a lower ratio of carbon to hydrogen in biodiesels [46]. By increasing the engine speed, HC emission also increases [25]. Figure 5b shows the levels of HC emissions. Also there is a significant reduction in the unburned hydrocarbon emission of diesterol (ethanol, diesel, and biodiesel) with respect to conventional diesel. The addition of 2% and 3% of ethanol and biodiesel, respectively, to diesel causes a high reduction in unburned hydrocarbon emissions. By increasing the addition of ethanol and biodiesel, the reduction trend grows slower [47]. Some studies have stated that the increase of HC emissions in biofuel and diesel fuel blends is caused by ethanol's higher evaporation temperature [48-50]. In a study on a four-cylinder direct injection engine (VGT), the results showed that using ethanol (E10, E20) blended with diesel caused the increase of HC emissions by increasing ethanol.

3.1.3. Carbon monoxide (CO) emission

The results of the statistical analysis of CO reached a meaningful level at 5%, which shows the effect of biodiesel, ethanol, and engine rotational speed on carbon monoxide emissions. The CO response level to biodiesel and engine rotational speeds variations are shown in Figure 7a. In different engine speeds with the increasing of biodiesel, CO was first reduced and then increased. This was due to the lower ratio of carbon to hydrogen in biodiesels or the higher oxygen content with respect to conventional diesel [51]. The final equation of coded factors is presented in Eq. 3.

$$CO = +0.94 - 0.32X_1 + 0.49X_2 + 0.37X_3 - 0.36X_1X_2 - 0.062X_1X_3 + 0.42X_1X_3 + 0.50X_1^2 \quad (3)$$

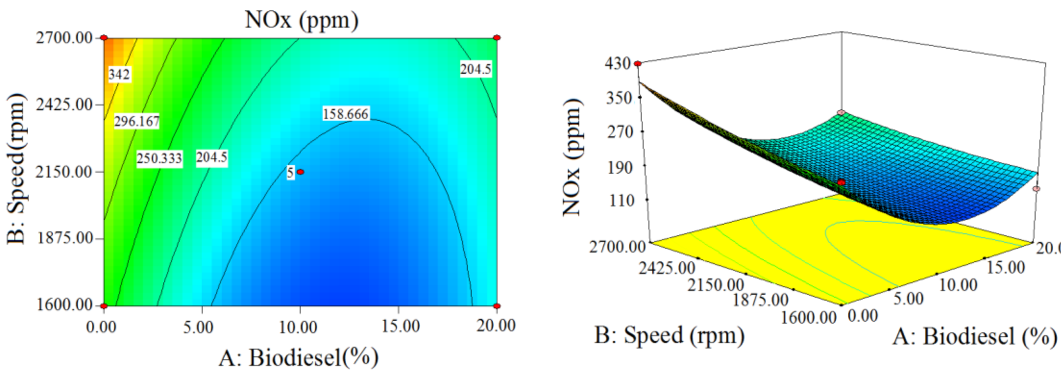


Fig. 4. The interactive effect of biodiesel and engine speed on NOx: (a) 3D response surface plot and (b) 2D contours plot.

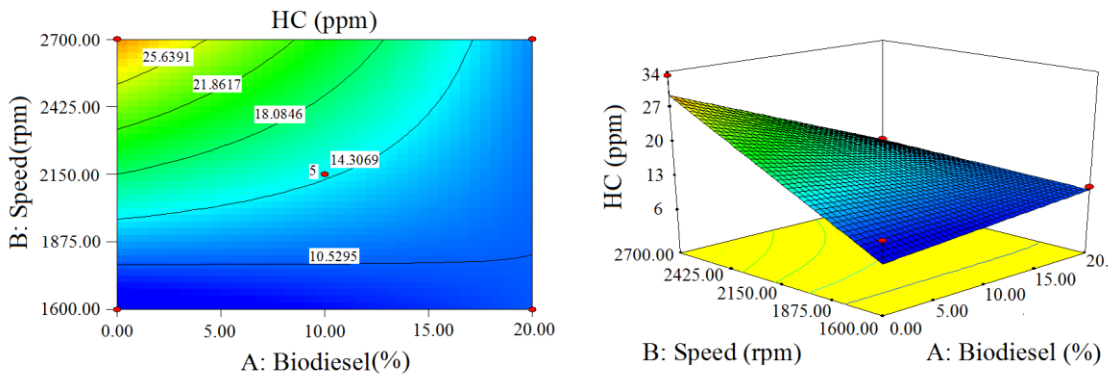


Fig. 5. The interactive effect of biodiesel and engine speed on HC: (a) 3D response surface plot and (b) 2D contours plot.

Ozsezen (2009) concluded that in waste palm oil and canola oil biodiesels, CO emission is reduced by 86.89% and 72.68%, respectively, relative to pure diesel [25]. In some studies, the average CO emission was determined to be 17.13% less than diesel [52]. CO formation is a function of incomplete combustion due to the lack of oxygen in the molecular structure of fossil fuels. When adding biodiesels to the fuel, CO emission is reduced because of more oxygen content in their molecular structure [45]. During the combustion of blended fuels, more oxygen is available; hence, by increasing the biodiesels in the blended fuels, CO emission is reduced relative to pure diesel [53]. Fontaras et al. (2009) concluded that in B50 and B100 biodiesels, CO emission increased by 54% and 95%, respectively [54]. However, the CO increases by increasing the engine speed in different ratios of biodiesels (Figure 6a). Figure 6b shows the levels of CO emissions for different ratios of biodiesels in various engine speeds. In many studies, the reduction of carbon monoxide emissions is reported by using biofuel and diesel blends [55-57]. A low combustion temperature may also cause the formation of carbon monoxide [58] Ethanol and biodiesel provide more oxygen for the combustion chamber, but the high evaporation of ethanol reduces the combustion chamber temperature and prevents oxidation of CO to CO_2, thus increasing the CO [59]. In another study on a four-cylinder direct injection engine, the CO increased by increasing the ethanol ratio in the fuel blend [58].

3.1.4. Carbon dioxide (CO_2) emission

The results of the statistical analysis of CO_2 reached a meaningful level at 5%. The CO_2 response level graph with respect to biodiesel and engine rotational speeds variations shows that by increasing biodiesel ratio in the fuel blend, CO_2 first decreased and then increased (Figure 7a). Equation 4 is obtained based on the coded parameters**:**

$$\begin{aligned} CO_2 = &+3.47 - 0.87X_1 + 1.11X_2 + 0.63X_3 \\ &- 0.99X_1X_2 - 0.17X_1X_3 \\ &+ 1.37X_2X_3 + 1.4X_1^2 \\ &+ 0.58X_2^2 - 0.24X_3^2 \end{aligned} \quad (4)$$

The CO_2 reduction is due to the higher viscosity of the biodiesel. Also biodiesel has lower carbon content with respect to pure diesel [41]. However, the CO_2 increases by increasing the engine speed in different ratios of biodiesels. Figure (7b) shows the levels of CO_2 emissions for different ratios of biodiesels in various engine speeds.

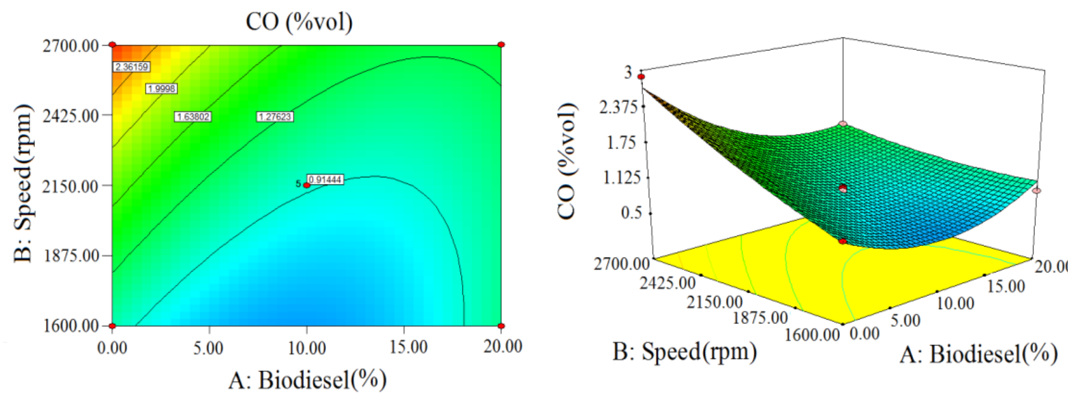


Fig.6. The interactive effect of biodiesel and engine speed on CO: (a) 3D response surface plot and (b) 2D contours plot.

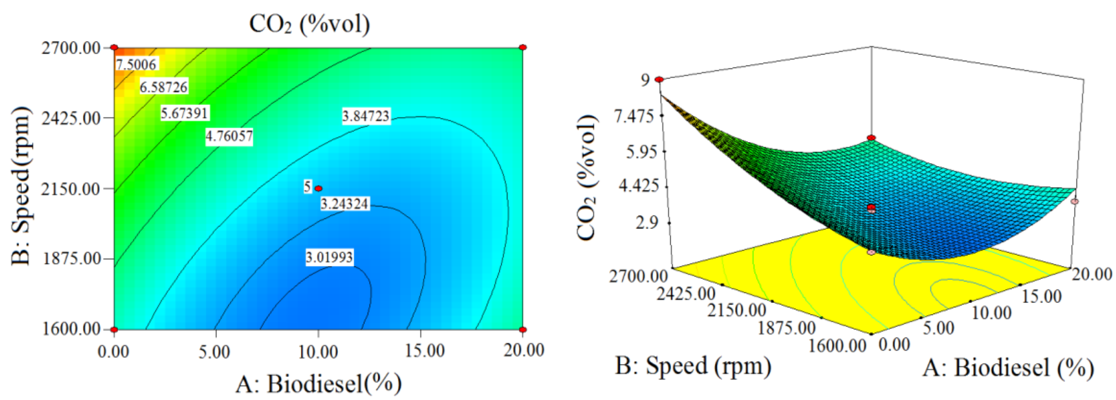


Fig.7. The interactive effect of biodiesel and engine speed on CO_2: (a) 3D response surface plot and (b) 2D contours plot.

3.2. Engine Performance Parameters

3.2.1. Specific Fuel Consumption (S.F.C.)

The results of the statistical analysis of specific fuel consumption did not reach to a meaningful level at 5%. This meant that despite the variations in the graph, different biodiesel fuel blends and engine rotational speeds variations had no effect on specific fuel consumption. The specific fuel consumption response level graph with respect to biodiesel and engine rotational speeds variations showed that by increasing biodiesel, specific fuel consumption first increased and then decreased (Figure 8a). The specific fuel consumption was maximum for B10 and minimum for B20. The results of the diesel engine performance parameters showed that increasing biodiesel fuel by up to 40% of volume, the fuel consumption and brake specific fuel consumption parameters were reduced, and by increasing biodiesel more than 40%, the fuel consumption increased [56]. Equation 5 is obtained base on the coded independent variables.

$$\begin{aligned} \mathrm{S.F.C} = {} & 358.36\mathrm{X}_1 - 136.17\mathrm{X}_2 - 336.91\mathrm{X}_3 \\ & + 87.61\mathrm{X}_1\mathrm{X}_2 - 707.33\mathrm{X}_1\mathrm{X}_3 \\ & - 212.50X_1^2 + 511.54X_2^2 \end{aligned} \quad (5)$$

Some researchers have concluded that increasing biodiesel ratio in fuel blended with diesel increases fuel consumption. This may occur because of the lower heating value of biodiesel. Another reason for the variation in specific fuel consumption can be a change in the combustion time due to the cetane number of biodiesel [60,61]. By increasing engine rotational speeds in different biodiesel ratios, the specific fuel consumption was reduced (the minimum value is related to 1875 to 2150 rpm), and then it increased at a higher rate (the maximum value at 2700 rpm). Figure 8b shows the level lines of specific fuel consumption for different ratios of biodiesels in various engine speeds. By increasing ethanol ratio in the fuel blends, specific fuel consumption was reduced with respect to pure diesel so that in fuel blends with 3% ethanol, the specific fuel consumption was minimum.

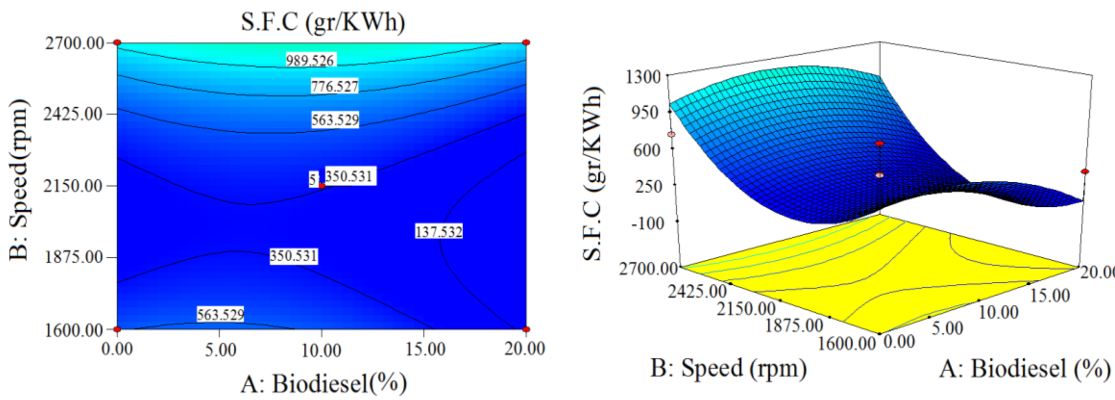


Fig. 8. The interactive effect of biodiesel and engine speed on S.F.C. (a) 3D response surface plot and (b) 2D contours plot.

3.2.2. Brake torque

The results of the statistical analysis of torque reached a meaningful level at 5%. The torque response level graph with respect to different biodiesel ratios and engine rotational speeds variations shows that by increasing biodiesel ratio, the torque increased with a constant slope and B20 reached its maximum value (Figure 9a). This can be caused due to the heating value difference between biodiesel and pure diesel [61]. Some studies have reported that despite a lower biodiesel heating value, the power and torque increased relative to pure diesel [38]. The second-order polynomial equation based on the coded values obtained using multiple regression analysis of the experimental data is presented as Eq. 6.

$$Torque = 17.50 + 0.11\,X_1 + -2.02X_2 + +0.78X_3 + 1.40X_1X_2 + 1.61X_1X_3 - 0.47X_2X_3 \quad (6)$$

Some researchers have concluded that biodiesel produced from cotton seeds resulted in a slight reduction in engine torque. This reduction in engine performance is mainly due to the lower heating value of biodiesel in comparison with neat diesel [62,63]. Aydin et al. (2010) reported that by adding the cottonseed oil methyl ester of B5, B20, B50, and B75 in the diesel fuel, the torque was reduced due to the high viscosity and low heating value of this oil [48]. Lapuerta et al. (2008) concluded that there were little differences in the effective torque of a four-cylinder, four-stroke diesel engine for waste cooking oil methyl ester (WCOM), ethyl ester (WCOE), and its combinations (i.e., WCOM30, WCOM70, WCOE30, WCOE70)[64]. Similar results were obtained in another study on the same diesel engine in full load for waste cooking oil biodiesel [65]. By increasing the engine speeds in different ratios of biodiesel, the torque was reduced to a constant slope. This was due to the reduced amount of air entering the cylinder at high speeds [61]. Figure 9b shows the level lines of torque for different ratios of biodiesels in various engine speeds.

3.2.3. Brake power

The results of the statistical analysis of power reached a meaningful level at 5%. The power response level graph with respect to different biodiesel ratios and engine rotational speeds variations showed that by increasing biodiesel, the power was reduced (minimum at B10) and then increased with a small slope; for B0 (pure diesel), it reached its maximum value (Figure 10a). Equation (7) is a second-order multinomial relation based on the variables derived from multivariate regression analysis of empirical data.

$$\text{Power} = 4.39 - 0.054\text{X}_1 + 0.32\text{X}_2 + +0.31\text{X}_3 - 0.21\text{X}_1\text{X}_2 + 0.24\text{X}_2\text{X}_3 + 0.13\text{X}_1^2 - 0.27\text{X}_3^2 \quad (7)$$

Most researchers have found that the actual power reduction is less than what they expected (due to biodiesel low heating value relative to diesel) [34]. Utlu et al. (2008) concluded that torque and power were reduced by 4.3% and 4.5%, respectively, due to the high viscosity and density and low heating value of biodiesel [26]. Murillo et al. (2007) observed that biodiesel reduced the power by 7.14% relative to diesel in a three-cylinder submarine engine in full load, and the biodiesel heating value was reduced by 13.5% relative to diesel [66]. The results of the present study showed that by increasing biodiesel, the engine power was reduced. By increasing engine rotational speeds in different biodiesel ratios, power was first increased (the maximum value has reached from 2150 rpm to 2425 rpm) and then reduced. Figure 10b shows the level lines of power for different ratios of biodiesels in various engine speeds. By increasing ethanol ratio in the fuel blends, the power first increased and then decreased.

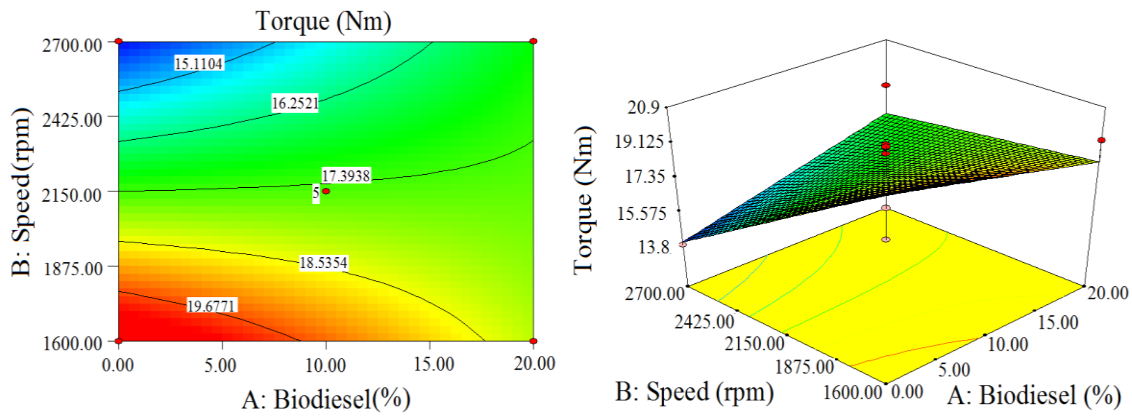
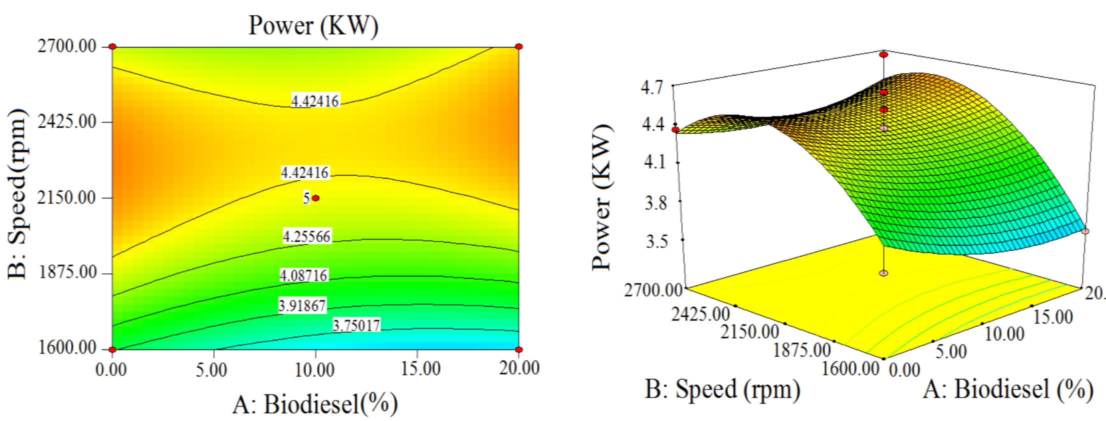


Fig. 9. The interactive effect of biodiesel and engine speed on Torque: (a) 3D response surface plot and (b) 2D contours plot.



(a) (b)

Fig. 10. The interactive effect of biodiesel and engine speed on Power: (a) 3D response surface plot and (b) 2D contours plot.

4. The optimum fuel blend

The response surface method obtained the optimum fuel blend of 2.21% ethanol and 10.26% biodiesel at the engine speed of 2657.98 rpm.

5. Conclusions

The advanced diesterol fuel consists of ethanol, diesel, and biodiesel. It solved some of the problems of diesel and biodiesel fuels, including viscosity and pour point in cold climates. The Jatropha biodiesel was produced from its pure oil by the conventional transesterification method. The results suggested an engine speed of 2657 rpm, a biodiesel ratio of 10.6%, and an ethanol concentration of 2.21% as the optimal values. The closest conditions to the optimum fuel blend were selected and compared to pure diesel with respect to engine performance and exhaust emissions. The results showed that Jatropha diesterol had 5% less NOx, 26.1% less HC, 1.33% less CO, and 9.6% more CO_2 emissions relative to pure diesel. The Jatropha biodiesel increased CO_2 emissions. Therefore, additional studies are needed to discover the reasons and find methods to reduce it. It is proposed to perform more studies on diesterol fuel using other plant oil biodiesels and bioethanol as well as measuring engine noise, vibration, and solid particle emissions when operating on the diesterol fuels.

References

[1] Sharma, A., Singh, Y., Gupta, S. K., Singh, N. K. (2021). Application of response surface methodology to optimize diesel engine parameters fuelled with pongamia biodiesel/diesel blends. *Energy sources, part A: Recovery, utilization, and environmental effects*, *43*(2), 133-144.

[2] Shojae, K., Mahdavian, M. (2018). Improving the combustion and emission characteristics of ISM 370 diesel engine by hydrogen addition and redesigning injection strategy. *Advances in environmental technology, 4*(2), 119-129.

[3] Ardebili, S. M. S., Solmaz, H., İpci, D., Calam, A., Mostafaei, M. (2020). A review on higher alcohol of fusel oil as a renewable fuel for internal combustion engines: Applications, challenges, and global potential. *Fuel, 279*, 118516.

[4] Calam, A. (2020). Effects of the fusel oil usage in HCCI engine on combustion, performance and emission. *Fuel, 262*, 116503

[5] Yusri, I. M., Mamat, R., Najafi, G., Razman, A., Awad, O.

I., Azmi, W. H., Shaiful, A. I. M. (2017). Alcohol based automotive fuels from first four alcohol family in compression and spark ignition engine: A review on engine performance and exhaust emissions. *Renewable and sustainable energy reviews, 77*, 169-188.

[6] Ardebili, S. M. S. (2020). Green electricity generation potential from biogas produced by anaerobic digestion of farm animal waste and agriculture residues in Iran. *Renewable energy, 154*, 29-37

[7] Ardebili, S. M. S., Khademalrasoul, A. (2020). An assessment of feasibility and potential of gaseous biofuel production from agricultural/animal wastes: a case study. *Biomass conversion and biorefinery*, 1-10.

[8] Solmaz, H. (2020). A comparative study on the usage of fusel oil and reference fuels in an HCCI engine at different compression ratios. *Fuel, 273*, 117775.

[9] Najafi, G., Ghobadian, B., Tavakoli, T., Yusaf, T. (2009). Potential of bioethanol production from agricultural wastes in Iran. *Renewable and sustainable energy reviews, 13*(6-7), 1418-1427.

[10] Ardebili, M. S., Ghobadian, B., Najafi, G., Chegeni, A. (2011). Biodiesel production potential from edible oil seeds in Iran. *Renewable and sustainable energy reviews, 15*(6), 3041-3044.

[11] Khedri, B., Mostafaei, M., Safieddin Ardebili, S. M. (2019). A review on microwave-assisted biodiesel production. *Energy sources, part A: Recovery, utilization, and environmental effects, 41*(19), 2377-2395.

[12] Azad, A. K., Rasul, M. G., Khan, M. M. K., Sharma, S. C., Mofijur, M., Bhuiya, M. M. K. (2016). Prospects, feedstocks and challenges of biodiesel production from beauty leaf oil and castor oil: a nonedible oil sources in Australia. *Renewable and sustainable energy reviews, 61*, 302-318.

[13] Portugal-Pereira, J., Nakatani, J., Kurisu, K. H., Hanaki, K. (2015). Comparative energy and environmental analysis of Jatropha bioelectricity versus biodiesel production in remote areas. *Energy, 83*, 284-293.

[14] Mofijur, M., Masjuki, H. H., Kalam, M. A., Hazrat, M. A., Liaquat, A. M., Shahabuddin, M., Varman, M. (2012). Prospects of biodiesel from Jatropha in Malaysia. *Renewable and sustainable energy reviews, 16*(7), 5007-5020.

[15] Yang, L., Takase, M., Zhang, M., Zhao, T., Wu, X. (2014). Potential non-edible oil feedstock for biodiesel production in Africa: a survey. *Renewable and sustainable energy reviews, 38*, 461-477.

[16] Ibrahim, S. M. A., Abed, K. A., Gad, M. S. (2014). An experimental investigation of diesel engine performance using jatropha biodiesel. *World applied sciences journal, 31*(6), 998-1003.

[17] Alshammari, A. M., Adnan, F. M., Mustafa, H., Hammad, N. (2011). Bioethanol fuel production from rotten banana as an environmental waste management and sustainable energy. *African journal of microbiology research*, *5*(6), 586-598.

[18] Fayyazi, E., Ghobadian, B., Mousavi, S. M., Najafi, G. (2018). Intensification of continues biodiesel production process using a simultaneous mixer-separator reactor. *Energy sources, part a: Recovery, utilization, and environmental effects, 40*(9), 1125-1136.

[19] Ardebili, S. M. S., Hashjin, T. T., Ghobadian, B., Najafi, G., Mantegna, S., Cravotto, G. (2015). Optimization of biodiesel synthesis under simultaneous ultrasound-microwave irradiation using response surface methodology (RSM). *Green processing and synthesis, 4*(4), 259-267.

[20] Marchetti, J. M., Miguel, V. U., Errazu, A. F. (2007). Possible methods for biodiesel production. *Renewable and sustainable energy reviews, 11*(6), 1300-1311.

[21] Crudo, D., Bosco, V., Cavaglià, G., Grillo, G., Mantegna, S., Cravotto, G. (2016). Biodiesel production process intensification using a rotor-stator type generator of hydrodynamic cavitation. *Ultrasonics sonochemistry, 33*, 220-225.

[22] Choedkiatsakul, I., Ngaosuwan, K., Assabumrungrat, S., Tabasso, S., Cravotto, G. (2015). Integrated flow reactor that combines high-shear mixing and microwave irradiation for biodiesel production. *Biomass and bioenergy, 77*, 186-191.

[23] Azad, A. K., Islam, M. R. (2012). A renewable alternative bio-fuel source from Jatropha Curcus seeds oil: performance and emission study for DI diesel engine. *International journal of advanced renewable energy research, 1*(2), 126-32.

[24] Banapurmath, N. R., Tewari, P. G., Hosmath, R. S. (2008). Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methyl esters. *Renewable energy, 33*(9), 1982-1988.

[25] Ozsezen, A. N., Canakci, M., Turkcan, A., Sayin, C. (2009). Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. *Fuel, 88*(4), 629-636.

[26] Utlu, Z., Koçak, M. S. (2008). The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions. *Renewable energy, 33*(8), 1936-1941.

[27] Piroonlerkgul, P., Laosiripojana, N., Adesina, A. A., Assabumrungrat, S. (2009). Performance of biogas-fed solid oxide fuel cell systems integrated with membrane module for CO_2 removal. *Chemical engineering and processing: process intensification, 48*(2), 672-682.

[28] Mofijur, M., Rasul, M. G., Hyde, J. (2015). Recent developments on internal combustion engine performance and emissions fuelled with biodiesel-diesel-ethanol blends. *Procedia engineering, 105*, 658-

664.

[29] Von Blottnitz, H., Curran, M. A. (2007). A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of cleaner production, 15*(7), 607-619.

[30] Gharehghani, A., Asiaei, S., Khalife, E., Najafi, B., Tabatabaei, M. (2019). Simultaneous reduction of CO and NOx emissions as well as fuel consumption by using water and nano particles in Diesel–Biodiesel blend. *Journal of cleaner production, 210*, 1164-1170.

[31] Cavalcante, K. S., Penha, M. N., Mendonça, K. K., Louzeiro, H. C., Vasconcelos, A. C., Maciel, A. P., Silva, F. C. (2010). Optimization of transesterification of castor oil with ethanol using a central composite rotatable design (CCRD). *Fuel, 89*(5), 1172-1176.

[32] Azadbakht, M., Ardebili, S. M. S., Rahmani, M. (2021). A study on biodiesel production using agricultural wastes and animal fats. *Biomass conversion and biorefinery*, 1-7.

[33] Ghobadian, B., Yusaf, T., Najafi, G., Khatamifar, M. (2009). Diesterol: an environment-friendly IC engine fuel. *Renewable energy, 34*(1), 335-342.

[34] Mirbagheri, S. A., Ardebili, S. M. S., Kiani, M. K. D. (2020). Modeling of the engine performance and exhaust emissions characteristics of a single-cylinder diesel using nano-biochar added into ethanol-biodiesel-diesel blends. *Fuel, 278*, 118238.

[35] Ghobadian, B., Rahimi, H., Khatamifar, M. (2006). Evaluation of engine performance using net diesel fuel and biofuel blends. In *the first combustion conference of Iran (CCT1). Tarbiat Modares University. February* (pp. 15-16).

[36] Park, S. H., Youn, I. M., Lee, C. S. (2010). Influence of two-stage injection and exhaust gas recirculation on the emissions reduction in an ethanol-blended diesel-fueled four-cylinder diesel engine. *Fuel processing technology, 91*(11), 1753-1760.

[37] Wu, F., Wang, J., Chen, W., Shuai, S. (2009). A study on emission performance of a diesel engine fueled with five typical methyl ester biodiesels. *Atmospheric environment, 43*(7), 1481-1485.

[38] Dorado, M. P., Ballesteros, E., Arnal, J. M., Gomez, J., Lopez, F. J. (2003). Exhaust emissions from a Diesel engine fueled with transesterified waste olive oil. *Fuel, 82*(11), 1311-1315.

[39] Lapuerta, M., Armas, O., Garcia-Contreras, R. (2007). Stability of diesel–bioethanol blends for use in diesel engines. *Fuel, 86*(10-11), 1351-1357.

[40] Lin, B. F., Huang, J. H., Huang, D. Y. (2009). Experimental study of the effects of vegetable oil methyl ester on DI diesel engine performance characteristics and pollutant emissions. *Fuel, 88*(9), 1779-1785.

[41] Basha, J. S., Anand, R. B. (2014). Performance, emission and combustion characteristics of a diesel engine using Carbon Nanotubes blended Jatropha Methyl Ester Emulsions. *Alexandria engineering journal, 53*(2), 259-273.

[42] Calam, A., Solmaz, H., Yılmaz, E., İçingür, Y. (2019). Investigation of effect of compression ratio on combustion and exhaust emissions in A HCCI engine. *Energy, 168*, 1208-1216.

[43] Ghobadian, B., Rahimi, H., Nikbakht, A. M., Najafi, G., Yusaf, T. F. (2009). Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network. *Renewable energy, 34*(4), 976-982.

[44] Hagos, F. Y., Ali, O. M., Mamat, R., Abdullah, A. A. (2017). Effect of emulsification and blending on the oxygenation and substitution of diesel fuel for compression ignition engine. *Renewable and sustainable energy reviews, 75*, 1281-1294.

[45] Awad, O. I., Mamat, R., Ali, O. M., Othman, M. F., Abdullah, A. A. (2017). Experimental study of performance and emissions of fusel oil-diesel blend in a single cylinder diesel engine. *International journal of engineering and technology, 9*(2), 138.

[46] Yasin, M. H. M., Mamat, R., Ali, O. M., Yusop, A. F., Hamidi, M. A., Ismail, M. Y., Rasul, M. (2017). Study of diesel-biodiesel fuel properties and wavelet analysis on cyclic variations in a diesel engine. *Energy procedia, 110*, 498-503.

[47] Oberoi, H. S., Vadlani, P. V., Saida, L., Bansal, S., & Hughes, J. D. (2011). Ethanol production from banana peels using statistically optimized simultaneous saccharification and fermentation process. *Waste management, 31*(7), 1576-1584.

[48] Aydin, H., Bayindir, H. (2010). Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. *Renewable energy, 35*(3), 588-592.

[49] Najafi, G., Ghobadian, B., Yusaf, T., Rahimi, H. (2007). Combustion analysis of a CI engine performance using waste cooking biodiesel fuel with an artificial neural network aid. *American journal of applied sciences, 4*(10), 756-764.

[50] Najafi, G., Ghobadian, B., Moosavian, A., Yusaf, T., Mamat, R., Kettner, M., Azmi, W. H. (2016). SVM and ANFIS for prediction of performance and exhaust emissions of a SI engine with gasoline–ethanol blended fuels. *Applied thermal engineering, 95*, 186-203.

[51] Noorollahi, Y., Azadbakht, M., Ghobadian, B. (2018). The effect of different diesterol (diesel–biodiesel–ethanol) blends on small air-cooled diesel engine performance and its exhaust gases. *Energy, 142*, 196-200.

[52] Pour, A. H., Ardebili, S. M. S., Sheikhdavoodi, M. J. (2018). Multi-objective optimization of diesel engine performance and emissions fueled with diesel-biodiesel-fusel oil blends using response surface method. *Environmental science and pollution research,*

25(35), 35429-35439.

[53] Singh, Y., Singla, A. (2015). Comparative analysis of jatropha and karanja-based biodiesel properties, performance and exhaust emission characteristics in an unmodified diesel engine. *Pollution, 1*(1), 23-30.

[54] Fontaras, G., Karavalakis, G., Kousoulidou, M., Tzamkiozis, T., Ntziachristos, L., Bakeas, E., Samaras, Z. (2009). Effects of biodiesel on passenger car fuel consumption, regulated and non-regulated pollutant emissions over legislated and real-world driving cycles. *Fuel, 88*(9), 1608-1617.

[55] Di, Y., Cheung, C. S., Huang, Z. (2009). Comparison of the effect of biodiesel-diesel and ethanol-diesel on the particulate emissions of a direct injection diesel engine. *Aerosol science and technology, 43*(5), 455-465.

[56] Mahla, S. K., Safieddin Ardebili, S. M., Mostafaei, M., Dhir, A., Goga, G., Chauhan, B. S. (2020). Multi-objective optimization of performance and emissions characteristics of a variable compression ratio diesel engine running with biogas-diesel fuel using response surface techniques. *Energy sources, part a: Recovery, utilization and environmental effects*, 1-18.

[57] Ardebili, S. M. S., Solmaz, H., Calam, A., İpci, D. (2021). Modelling of performance, emission, and combustion of an HCCI engine fueled with fusel oil-diethylether fuel blends as a renewable fuel. *Fuel*, *290*, 120017.

[58] Senthilraja, R., Sivakumar, V., Thirugnanasambandham, K., Nedunchezhian, N. (2016). Performance, emission and combustion characteristics of a dual fuel engine with Diesel–Ethanol–Cotton seed oil Methyl ester blends and Compressed Natural Gas (CNG) as fuel. *Energy, 1*12, 899-907.

[59] Sukjit, E., Herreros, J. M., Dearn, K. D., García-Contreras, R., Tsolakis, A. (2012). The effect of the addition of individual methyl esters on the combustion and emissions of ethanol and butanol-diesel blends. *Energy, 42*(1), 364-374.

[60] Devarajan, Y., Beemkumar, N., Ganesan, S., Arunkumar, T. (2020). An experimental study on the influence of an oxygenated additive in diesel engine fuelled with neat papaya seed biodiesel/diesel blends. *Fuel, 268*, 117254.

[61] Khalife, E., Tabatabaei, M., Demirbas, A., Aghbashlo, M. (2017). Impacts of additives on performance and emission characteristics of diesel engines during steady state operation. *Progress in energy and combustion science, 59*, 32-78.

[62] Carraretto, C., Macor, A., Mirandola, A., Stoppato, A., Tonon, S. (2004). Biodiesel as alternative fuel: Experimental analysis and energetic evaluations. *Energy, 29*(12-15), 2195-2211.

[63] He, Y., Bao, Y. D. (2005). Study on cottonseed oil as a partial substitute for diesel oil in fuel for single-cylinder diesel engine. *Renewable energy, 30*(5), 805-813.

[64] Lapuerta, M., Herreros, J. M., Lyons, L. L., García-Contreras, R., Briceño, Y. (2008). Effect of the alcohol type used in the production of waste cooking oil biodiesel on diesel performance and emissions. *Fuel, 87*(15-16), 3161-3169.

[65] Enweremadu, C. C., Rutto, H. L. (2010). Combustion, emission and engine performance characteristics of used cooking oil biodiesel—a review. *Renewable and sustainable energy reviews, 14*(9), 2863-2873.

[66] Murillo, S., Miguez, J. L., Porteiro, J., Granada, E., Moran, J. C. (2007). Performance and exhaust emissions in the use of biodiesel in outboard diesel engines. *Fuel, 86*(12-13), 1765-1771.