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Research Article

Investigation and Ranking of the Effect of Biodiesel Produced from Safflower Oil by the Hydrodynamic Method in Diesel Generator Engine Using TOPSIS Method

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ABSTRACT

To investigate the possibility of using fuel for plant origin in a diesel generator, safflower methyl ester was prepared and used as a biodiesel. In this research, biodiesel was produced through a transesterification reaction using a hydrodynamic reactor, which increased the reaction efficiency and reduced fuel production time. Upon increasing the reaction time from 30 seconds to 60 seconds, the reaction performance increased by 5.5 %. Then, its important features complied with ASTM D-6751 standard. The performance and pollution indices of the diesel generator engine were tested with compounds B0, B20, B50, B80 and B100. The results of short-term engine tests showed that by increasing the share of biodiesel to 20 %, CO emissions were reduced by 21 % compared to pure diesel fuel, but the amount of NO_X increased by 0.82 % compared to diesel. Also, the use of 20 % volume of biodiesel in the fuel composition increased the thermal efficiency of braking, braking power, and braking torque of fuel, compared to diesel. Also, the specific fuel consumption of B20 was reduced by 2 %, which is very important economically. Finally, the TOPSIS analysis illustrated that B50 fuel outperformed pure diesel fuel and other listed fuel combinations.

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1. INTRODUCTION

With the rising population around the world, the use of fossil fuels, mainly in the transportation sector, has been soaring. Diesel engines are now considered an essential part of the propulsion of various vehicles. Today, however, diesel engines are considered as one of the main consumers of fossil fuels and hence, one of the important causes of noise and environmental pollution [1]. Today, because of the fast depleting nature of non-renewable fuel sources and the rise of greenhouse gas emissions owing to the combustion of these fuels, finding that can be cost-effective, renewable, and efficient with less greenhouse gas emissions is of particular importance [2]. Alternative fuels must come from cheap, renewable, affordable, and environmentally friendly sources. One of the most predominant sources of alternative fuels is biofuels. These fuels are used as liquid or gas in the transportation sector [3]. Biofuels generated from existing sources such as wood waste, plant species, municipal solid waste, aquatic plants, algae, and animal waste produce lower gas emission than fossil fuels [4].

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Biodiesel is one of the most suitable substitute fuels that can be a good alternative to diesel fuel [5]. It is a renewable fuel with high combustion efficiency, less pollutant gases with degradability in the environment, and suitable lubrication properties [6, 7]. Biodiesels are also characterized by a large amount of cetane, less smoke, less sulfur, and non-toxicity compared to diesel; therefore, it is more popular than diesel [8].

To use vegetable oils and animal fats directly as a source of energy in internal combustion engines and to ensure proper combustion conditions, it is necessary to break the molecular structure of these sources into simpler and balanced components because, otherwise, it will damage engine components [9, 10]. To this end, molecules of oil or fat compounds play a part in the reaction with alcohol, including ethanol or methanol, in the presence of an acidic or alkaline reactant, and the OH group in the used alcohol replaces the hydrocarbon chain in the oil. As a result, esters form with a new molecular structure, called fatty acid methyl esters, which are very similar to Diesel No. 2 [11]. So far, various methods have been proposed for biodiesel production including microemulsion, pyrolysis, and transesterification. The biodiesel obtained by microemulsion or pyrolysis method, because of its low cetane number, could yield incomplete fuel combustion and not be suitable [12]. Among the biodiesel production methods, the transesterification method is the best

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common method and it aims to reduce oil viscosity when triglyceride and alcohol react with each other [13]. In biodiesel production, with the help of conventional reactors, such problems as long production time, high production cost, low production efficiency, etc. need to be addressed in the design and construction of biodiesel production systems to make biodiesel fuel production more efficient and economical. In recent years, many types of research have been conducted on the development of various technologies for intensifying biodiesel production in order to eliminate or reduce some of the problems related to biodiesel production using conventional methods. These technologies include new reactors or a combination of reactors that intensify reactions such as turbulence, heat transfer, and mass transfer between two liquid phases in the biodiesel production process [14]. The use of hydrodynamic cavitation is one of these new technologies that has received much attention in recent years [15]. Biodiesel production with the assistance of hydrodynamic technology is a method with high potential on an industrial scale which is easier to develop than other methods [16]. The use of hydrodynamic cavitation has good energy efficiency and shortens the reaction time by consuming less energy than conventional mechanical methods. In this method, energy equivalent to half of the mechanical method is required which is a combination of two reaction phases using variable pressure. Cavitation is generated by fluid flow under controlled conditions through simple geometries such as venturi tubes and perforated plates. Given that the pressure of the fluid approaches the vapor pressure, large cavities form in the fluid, which subsequently fluctuate, causing the pressure and temperature to rise. As a result, immiscible liquids mix better and the transesterification process is enhanced [17]. In a study on biodiesel production from safflower seed oil by potassium hydroxide catalyst, Hosseinzadeh et al. (2013) reported that upon using hydrodynamic cavitation, biodiesel was obtained in optimum conditions [15].

The sharpest contrast between biodiesel and diesel compounds is their oxygen content. The oxygen content of diesel is zero, whereas biodiesel contains 10 to 12 % weight of oxygen, which reduces the emission of pollutants such as Particulate Matter (PM), Unburned Hydro-Carbons (UHC), and Carbon Monoxide (CO). Also, a high biodiesel cetane number can help shorten the ignition delay in a diesel engine [18]. Biodiesel is a long-chain fatty acid methyl or ethyl ester that is produced from biosources such as oils or fats from animals and vegetables and can be used instead of diesel in compression combustion engines without the need for major modifications [19].

In a study, El Morsi et al. (2019) examined biodiesel produced from a combination of kitchen waste oils, jatropha, palm, and algae using a transesterification process in single-cylinder diesel engines at 10 and 20 % by volume. The results showed that CO, CO_2, HC, and smoke emissions were lower for B10 and B20 than diesel, but NO_X increased slightly for all Bx's compared to diesel [20]. Nedayali and Shirneshan (2016) evaluated the effect of mixtures of biodiesel and diesel on engine performance characteristics (braking power, braking torque, braking thermal efficiency, and BSFC) in a diesel-electric motor. The results of this study exhibited an increase in braking power, braking torque, braking thermal efficiency, and a decrease in BSFC at higher engine loads for all fuel mixtures [21].

Safflower plant, scientifically called (*Carthamus Tinctorius L*), is an annual herbaceous plant whose flowers are yellow to red depending on the type of plant and each has 20 to 100 flowers and each produces a seed. The presence of wild species scattered throughout the country shows the good adaptation of this plant to the climatic conditions of Iran. Relative tolerance to soil salinity and air dryness, low moisture requirement, and high-quality oil are the noticeable features of safflower. In general, safflower seeds, depending on their genotype, contain 25 to 45 % oil, of which more than 90 % of fatty acids are unsaturated such as linoleic and oleic acid. Safflower with strong and long roots can absorb and consume water from the depths of the earth, and the prickly leaves and thorny organs create the least evaporation in the plant [22].

In the present study, safflower seed, which is native to Iran, was used for biodiesel production due to the mentioned advantages. Hydrodynamic cavitation reactors require less energy, lower sensitivity, lower production cost, and lower temperature than conventional reactors used to convert oil to biodiesel in the transesterification process [23, 24]. In short, much research has been done to investigate the emission and performance parameters of the engine with biodiesel fuel, but almost no research has been done to investigate the parameters of the engine with biodiesel from safflower oil using the hydrodynamic cavitation reactor. In this study, biodiesel was produced continuously using safflower oil and hydrodynamic cavitation reactor, and considering its various mixtures with diesel No. 2 common in Iran in the diesel generator engine, it was used to evaluate the engine performance indicators such as braking power, braking torque, BSFC, braking thermal efficiency, and exhaust gas temperature and engine pollution indicators, e.g., nitrogen oxides and carbon monoxide emissions, and the results were compared with pure diesel fuel.

2. EXPERIMENTAL

2.1. Raw materials and detectors

In the present study, the transesterification method was used. The required oil for biodiesel production was obtained from safflower seeds. The alcohol used was high purity methanol (99 %) and the catalyst used in the biodiesel production process was potassium hydroxide (KOH- 99.8 %). n-Hexane (96 %) and phenolphthalein (98 %) were also used as solvent aid and detector, respectively.

2.2. Extraction and preparation of oil

Safflower seeds were placed in an oven at 65 °C for 24 hours until their moisture content reached about 7 %. The grains were then ground using a laboratory mill. Soxhlet apparatus and normal hexane solution were employed to extract the oil. For this purpose, in 5 steps, oil was extracted each time a certain amount of ground grains (100 g) was placed in the Soxhlet machine and by controlling the solvent temperature, residence time, and solvent volume. Finally, the obtained oil was passed through a filter to remove solid particles [25]. Finally, 140 grams of oil was obtained, which showed a return of 28 % of oil.

2.3. Determining the acidity of safflower oil

Since fatty acids are weak acids, it is necessary to use strong alkalis such as potassium hydroxide to titrate them. If the percentage of free fatty acids is higher than 0.5 %, the ester exchange method cannot be used directly and a pre-refining step must be performed, which is the esterification step. To assess the acidity of the sample, 20 g of the oil tested in Erlenmeyer was weighed as 300 ml and then, 50 ml of solvent was added and stirred until the oil sample was completely dissolved. 2 ml of phenolphthalein was added and titrated with 0.1 mol/l potassium hydroxide until it turned a solid constant pink color. The solution was shaken vigorously during titration so that the pink color lasted for 30 seconds. Formulas (1) and (2) were employed to calculate the acid number and percentage of free fatty acids, respectively.

$$\text{Acid number} = \frac{\text{PC} \times \text{NP} \times 56.1}{\text{W}} \quad (1)$$

$$\text{Percentage of free fatty acids} = \frac{\text{PC} \times \text{NP} \times 28.2}{\text{W}} \quad (2)$$

where PC is the average of potassium consumed (ml), NP is the normality of the potassium solution (mol/L), and W is the weight of the oil. For transesterification testing, the oil acidity must be greater than 3 %.

2.4. Characteristics of biodiesel fatty acids produced from safflower

The characteristics of biodiesel are undeniably affected by the type of fatty acids. Recognition of these characteristics is very effective in determining the characteristics of biodiesel fuels [26]. Biodiesel is composed of some fatty acid monoesters, and the presence of the weight percentage of each one of them in biodiesel fuel affects its thermophysical properties. In other words, the properties of biodiesel fuel depend on the monoesters of its constituent fatty acids, the most important of which are the esters of palmitic, stearic, oleic, and linoleic fatty acids that directly affect the combustion process and engine performance [27]. Short-chain saturated fatty acids such as stearic and palmitic have a greater effect on engine power output, and long-chain unsaturated fatty acids such as oleic and linoleic have less significant effect on engine power. Therefore, biodiesel fuel from the oils with more saturated and less unsaturated fatty acids can increase power production by the engine [28]. Safflower oil is a good source for biodiesel owing to its high fatty acids. Some physical and chemical characteristics of safflower oil are shown in Table 1 [22].

Table 1. Physical and chemical characteristics of safflower oil

Properties	Normal limits	Unit
Viscosity at 40 °C	28.3	mm^2/s
Density at 15 °C	0.92	kg/m^3
Flash point	226	°C
Acid number	0.4-10	mg KOH/g Oil
Base number	186-194	-
Ionic number	130-150	-
Percentage of non-soapy ingredients	0.3-1.3	(wt %)
C18: 2 (Linoleic acid)	71-75	(wt %)
C18: 1 (Oleic acid)	16-20	(wt %)
C16: 0 (Palmitic acid)	6-8	(wt %)
C18: 0 (Stearic acid)	2-3	(wt %)

2.5. Hydrodynamic cavitation setup

The laboratory system required in this study was designed such that KOH and methanol would be first mixed with a magnetic stirrer model MR3001 made by the German company Heidolph and combined with safflower oil. The resulting solution was then injected into the hydrodynamic cavitation reactor by the Hydolf 5206 peristaltic pump. The reactor used in this study consisted of a transparent polycarbonate stator to observe the process, a stainless-steel perforated rotor to produce bubbles, and an electric motor to generate propulsion. The specifications of the reactor components are given in Table 2.

Table 2. Characteristics of the hydrodynamic reactor

Parameter	Value
Rotor length (m)	0.08
Rotor density (g/l)	905
Rotor diameter (m)	0.09
Number of holes	40
Stator diameter (m)	0.097
Electric-motor power (W)	75
Hole diameter (m)	0.004
Stator length (m)	0.09
Electric-motor rotational speed (rpm)	3200

2.6. Transesterification

To increase the reaction rate, the catalyst molecules must be homogeneously available to the oil and methyl hydrate molecules. For this reason, to increase the solubility of the catalyst used, potassium hydroxide and methanol were first combined with a magnetic stirrer and then, introduced into the methanol reservoir. Simply put, the catalyst and methanol were prepared before the transesterification reaction. In the next step, the desired solution is transferred into the chamber along with safflower oil. In this case, the combined solution rotates between the rotor and the stator using centrifugal force, and the rotation speed of the rotor ranges between 1000 and 3000 rpm. The holes in the rotor cause a sudden decrease in pressure, yielding a hole in the solution. As a result, at lower temperatures, the mass transfer between safflower oil and methanol increases. Following the completion of the transesterification reaction, methyl ester (biodiesel), glycerin, and some excess alcohols were the reaction products.

The glycerin phase was denser than the biodiesel phase and precipitated after a while. After precipitating glycerol, this phase was separated using a separating funnel [29]. The reason for choosing this method is its simplicity and low cost. After the settling step, the resulting biodiesel was washed 3 times with water containing 1 % by volume of phosphoric acid (H_3PO_4) to remove excess products such as glycerol, catalyst, and soap formed. Transparency of laundry wastewater remains a good measure of the completion of the work. Finally, after biodiesel purification, vacuum distillation was used to dry it [30]. The production steps of biodiesel using the hydrodynamic reactor are shown in Figure 1.

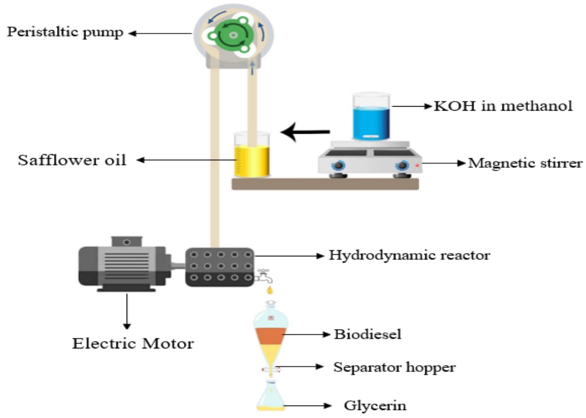

Figure 1. Schematic diagram of the hydrodynamic device

2.7. Calculation of methyl ester conversion and biodiesel performance

The weight of the biodiesel phase of each sample was measured after separation using a digital scale. Then, the exact amount of fatty acid esters was determined using gas chromatography (Claus 580 GC model, Perkin Elmer Co, USA) according to ASTM D6751 standard. Equation (3) was used to calculate the FAME performance [31, 32].

$$\text{FAME}\ \% = \frac{\sum A - A_{IS}}{A_{IS}} \times \frac{M_{IS}}{M} \times 100 \quad (3)$$

where $\sum A$ = The sum of the levels below the peaks; (μV×sec), A_{IS} = The sub-peak level corresponding to the internal standard; (μV×sec), C_{IS} = Internal standard solution concentration; (mg/ml), V_{IS}= Volume of use of internal standard solution; (ml) and M = Biodiesel weight for decomposition in GC (mg).

2.8. Diesel engine generator

The diesel generator engine used in this research consists of two parts: the engine and the generator. The engine part includes a 4-stroke, 12-cylinder, and direct injection engine equipped with a supercharger. This engine is a model (3412C TA) with a maximum engine power of 537 kW at 1800 rpm. The generator part is made by Caterpillar Company, which is connected to the central processor that can display the amount of output voltage, power, and motor speed on the control panel by processing data. The specifications of the diesel generator engine listed in Table 3 are shown.

Table 3. Specifications of the diesel generator engine

Engine type	**Diesel power generator CAT3412**
Cylinder number	12
Bore (mm)	137
Stroke (mm)	154
Cooling system	Water-cooled
Rated engine speed (rpm)	1800
Aspiration	Turbocharged-After cooled
Governor	Mechanical
Compression ratio	13:01
Starting motor	24 V/7 Kw

3. METHOD

3.1. Methodology

To assess the performance and pollution of diesel generator engine using biodiesel produced from safflower oil with the help of hydrodynamic cavitation and compare it with conventional diesel fuel, different ratios of biodiesel were combined with diesel as independent variables by volume. These compounds contain 0 %, 20 %, 50 %, 80 % and 100 % biodiesels based on volume, which are called B0, B20, B50, B80 and B100, respectively. Each fuel was tested at full dynamometer load and a constant speed of 1530 rpm and their effects on dependent variables such as engine pollution indices such as NO_X and CO emissions and engine performance indices such as Braking power, braking torque, BSFC, exhaust gas temperature, and braking thermal efficiency were investigated. This experiment was analyzed in a completely randomized design with three replications. The mean comparison test was performed by the LSD method. SPSS software was employed for statistical analysis.

3.2. Multi-index decision-making method

TOPSIS is a multi-criteria decision-making method used to select the best option based on the number of criteria [33].

The steps to solve the problem using the TOPSIS method are as follows [34]:

<u>Step One:</u> After forming a decision matrix to evaluate the options based on the number of criteria, the dimensionless matrix is formed by Equation (4) using the vector method.

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \quad (4)$$

<u>Step Two:</u> At this stage of the TOPSIS method, the normal matrix created must be balanced. For this purpose, by using Equations (5) and (6), the weight of each criterion is multiplied in all subsets of that criterion and the weight of the criteria must be determined in advance.

$$W_i = \frac{r_i}{\sum_{i=1}^{n} r_i} \quad (5)$$

$$\sum_{i=1}^{n} W_i = 1 \quad (6)$$

$$V_{ij} = r_{ij} \times W_{n\times m} = \begin{matrix} V_{11} & V_{1j} & V_{1n} \\ \vdots & \vdots & \vdots \\ V_{m1} & V_{mj} & V_{mn} \end{matrix} \quad (7)$$

<u>Step Three:</u> Positive Ideal Point (PIS) and Negative Ideal Point (NIS) are calculated next. At this step, for each index, a positive ideal and a negative ideal were obtained through Relations (8) and (9), respectively.

$$PIS = \{(\max V_{ij} | j \in J), (\min V_{ij} | j \in J) \, | i = 1, 2, \dots, 3\} = \{V_1^+, V_2^+, \dots, V_j^+, \dots, V_n^+\} \quad (8)$$

$$NIS = \{(\max V_{ij} | j \in J), (\min V_{ij} | j \in J) \, | i = 1, 2, \dots, 3\} = \{V_1^-, V_2^-, \dots, V_j^-, \dots, V_n^-\} \quad (9)$$

<u>Step Four:</u> At this step, the relative proximity of each option to the ideal solution was calculated. The Euclidean distance of each method from the positive and negative ideals was calculated through Formulas (10) and (11), respectively.

$$d_{i+} = \{\sum j^n = 1^{(V_{ij}-V_j^+)^2}\}^{0.5}; \quad i = 1, 2, \dots, m \quad (10)$$

$$d_{i-} = \{\sum j^n = 1^{(V_{ij}-V_j^-)^2}\}^{0.5}; \quad i = 1, 2, \dots, m \quad (11)$$

<u>Step Five:</u> This step is to evaluate the ideal solution. At this point, the relative proximity of each method to the ideal solution was calculated using Equation 12 for this purpose.

$$C_i = \frac{d_{i-}}{((d_{i+}) + (d_{i-}))}; \quad 0 \le c_i \le 1; \quad i = 1, 2, \dots, m \quad (12)$$

<u>Step Six:</u> Ranking based on the value of C_i is done between zero and one. The closer this value is to one, the closer the solution is to the ideal answer and the better the solution is.

4. RESULTS AND DISCUSSION

4.1. Characteristics of produced biodiesel

The biodiesel characteristics of vegetable oils depend significantly on the fatty acid chains in the feed used. For methyl ester to be introduced as biodiesel, some of its characteristics must meet reference standards. Some characteristics of biodiesel achieved from SFO sing the hydrodynamic reactor including density, viscosity, acid content, flash point, iodine content, free glycerin, and cetane number according to ASTM standard D6751 were measured and the outcomes were compared with EN 14214 (Table 4). The results indicate that most of the characteristics comply with the ASTM standard.

In the process of producing biodiesel using a hydrodynamic reactor, the reaction time was increased from 30 seconds to 60 seconds, which led to a 5.5 % increase in the process. As a result, reaction time is a major factor in biodiesel production in this way. Also, the efficiency of methyl ester produced by the mentioned method was higher than the conventional method. The analysis of data showed that by increasing the distance between the stator and the rotor, the amount of solution mixing was reduced, which attenuated the performance of the biodiesel production process. The optimum yield of biodiesel production from safflower oil was 11.89 %, for which the distance between the stator and the rotor was 53.1 cm, reaction time was 63.88 seconds, catalyst concentration was 0.94 %, and the molar ratio of alcohol to oil was 1: 8.36.

Table 4. Some physicochemical characterization of biodiesel from SFO

Properties	Unit	EN 14214	ASTM D6751	Methyl ester
Ester content	% (m/m)	< 96.5	-	95.9
Density at 15 °C	g/cm^3	0.86–0.9	-	0.87
Kinematic viscosity at 40 °C	mm/s	3.5–5.0	1.9–6.0	4.52
Iodine number	g Iodine/100 g oil	< 120	-	117.47
Cetane number	-	> 51	> 47	48
Flash point	°C	> 101	> 130	157
Acid number	mgKOH/g	< 0.5	< 0.5	0.37
Free glycerin	% mass	0.02	-	0.017
Total glycerin	% mass	0. 24	-	0.25

4.2. NO_X emission

Figure 2 shows the changes in nitrogen oxides of biodiesel fuel compounds with the coefficient of determination (R^2=0.9575) and standard error (SE=6.7954). As shown earlier, the incremental percentage of NO_X emissions from B0 is minimal in B20 and maximal in B100. Following an increase in the amount of biodiesel in fuel content, the amount of NO_X increases as well. Therefore, the amount of NO_X in B100 compared to B0 increases by 14.5 %. Nitrogen Oxide (NO) is obtained by the combustion of hydrocarbons inside the engine combustion chamber. As smoke leaves the engine and communicates with the air, much more oxygen becomes available to NO, allowing for the production of nitrogen dioxide (NO_2). Therefore, high temperature and oxygen are the two principal factors in the formation of nitrogen oxides [33]. Since biodiesel fuel contains 10-12 % oxygen, it is not available [34] because it increases nitrogen oxides in two ways. First, as the share of biodiesel in the compound increases, the oxygen content of the compound also increases and more oxygen goes into contact with nitrogen, which leads to the production of nitrogen oxides. Second, as the oxygen content of the fuel increases, the ignition temperature decreases and the ignition time delay decreases. Therefore, it produces high temperatures due to combustion, thus providing a good opportunity for oxygen and nitrogen to react and produce nitrogen monoxide (NO) [35]. Most researchers have found that using biodiesel and diesel simultaneously increases NO_X due to the presence of much more oxygen in biodiesel than diesel [18, 36]. Hassanian et al. (2005) reported the same results for the effect of biodiesel percentage on NOx emission [37].

4.3. Carbon monoxide emissions (CO)

Figure 3 indicates the emission of CO pollutants from different percentages of biodiesel with a determination coefficient (R^2=0.8571) and a standard error (SE=0.000667). The results illustrated that the emission of CO pollutants in biodiesel fuels was significantly lower than pure diesel. Therefore, the amount of CO emission in B100 fuel compared to B0 fuel was reduced by 45.5 %. CO is a colorless, odorless gas that is dangerous to humans and animals, even at very low concentrations. CO is produced when the amount of oxygen in the combustion of organic matter is low. CO production and the presence of oxygen in an internal combustion engine are inversely related [20, 38]. As a result, less carbon monoxide is produced during combustion. Also, the ratio of carbon to hydrogen in biodiesel is lower than diesel [39, 40]. Therefore, this fact can be another reason for reducing CO emissions. Hosseinzadeh et al. reported the effect of biodiesel produced from safflower oil by ultrasonic waves on a diesel generator engine and reported that following an increase in percentage of biodiesel in fuel mixtures, CO emission decreased [41].

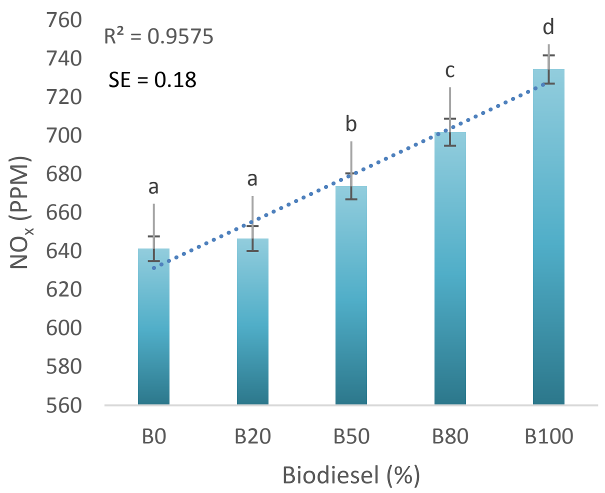

Figure 2. The effect of increasing biodiesel on NO_X emissions

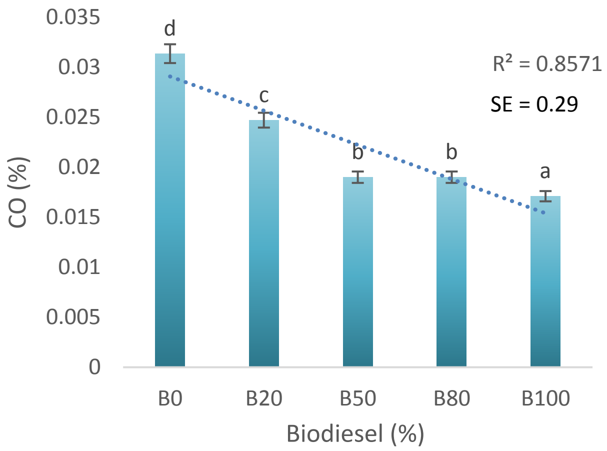

Figure 3. The effect of increasing biodiesel on CO emissions

4.4. Brake power

Figure 4 shows the braking power changes with the increasing value of Bx for different fuel combinations with the determination coefficient (R^2=0.8295) and standard error (SE=1.105037). Changes in engine braking power relative to different percentages of biodiesel are a quadratic function that is maximum at point B50 and minimum at point B100 (Equation 4). The results illustrated that upon increasing biodiesel content in fuel from B0 to B50, the braking power increased, and with increasing the percentage of biodiesel from B50 to B100, the braking power decreased. The reason for the increase in power in B50 is high fuel consumption and the presence of oxygen content, which causes a more complete combustion [42]. The reason for the decrease in power upon an increase in biodiesel content is the low thermal value of biodiesel [43]. Also, the viscosity of biodiesel is higher than diesel, which leads to incomplete automation of fuel in the combustion chamber and decreases the braking power of the engine [44]. Pure biodiesel at full load compared to pure diesel had a 3.7 % reduction in power owing to a decrease in the fuel thermal value. Murillo et al. reported that at full load, biodiesel power was reduced by 14.4 % compared to diesel fuel. They also concluded that the biodiesel calorific value was 13.5 % lower than diesel [45]. Xue et al. noted in a review study that the use of a low percentage of biodiesel in combination with diesel slightly reduced power and this reduction was not significant for the driver [18].

$$y = -1.5045X^2 + 8.102X + 92.701 \tag{13}$$

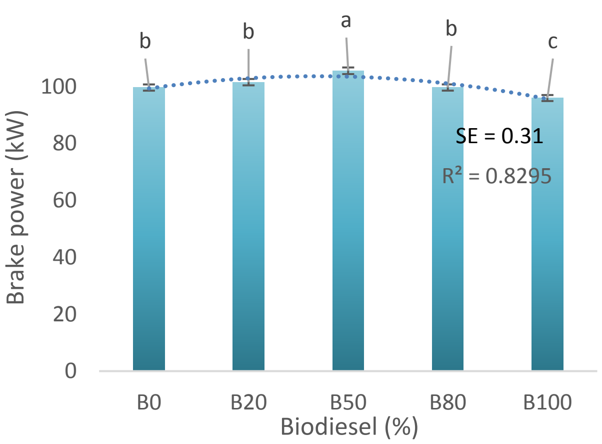

Figure 4. Effect of biodiesel content in fuel on the engine braking power

4.5. Brake torque

Figure 5 illustrates the variation of braking torque with the increasing biodiesel content for different fuel combinations with the coefficient of determination (R^2=0.7556) and standard error (SE=7.389837). The variation of braking torque to different percentages of biodiesel is a quadratic function which is maximum at point B50 and minimum at point B100 (Equation 5). The results illustrated an increase in braking torque with an increasing index value of Bx to B50 and then, with increasing the percentage of biodiesel, the amount of braking torque decreased. The energy release process for B100 is relatively slow due to its high cetane number, which lowers the pressure peak. The low thermal value of biodiesel also reduces the effective medium pressure. Based on the literature review, as the force applied to the surface of the piston decreased, the torque exerted by this force on the crankshaft is also reduced [46]. Therefore, the engine torque using pure biodiesel is less than pure diesel. In other words, oxygen of biodiesel content in the fuel improved the combustion process and complete combustion. As a result, more energy is released, increasing the average pressure inside the combustion chamber [47], which increases the power and torque produced for B50. Pure biodiesel at full load compared to pure diesel decreased by 5.27 % and B50 showed a 4.34 % increase in torque. Lin et al. reported that the maximum and minimum power and torque differences between diesel and eight types of vegetable oil methyl esters were 1.49 and 0.64, 1.39 and 1.25 percent, respectively. This is owing to high viscosity, high specific fuel consumption, high oxygen content, and high biodiesel ignition [48]. Shirneshan et al. reported in a study that the braking torque increased as the engine load increased because increasing the temperature of combustion led to more complete combustion at higher loads [49].

$$y = -7.5097X^2 + 36.424X + 589.15 \tag{14}$$

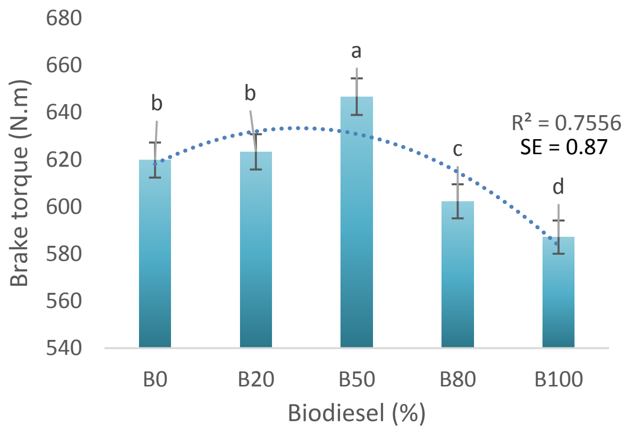

Figure 5. Effect of biodiesel content in fuel on the diesel engine output torque

4.6. Brake Special Fuel Consumption (BSFC)

The values of BSFC at full load for different percentages of biodiesel with the coefficient of determination (R^2=0.9948) and standard error (SE=9.853518) are shown in Figure 6. Changes in brake-specific fuel consumption relative to different percentages of biodiesel are a quadratic function that is minimum at point B20 and maximum at point B100 (Equation 6). As the share of biodiesel in fuel mixtures increases, the specific fuel consumption increases because biodiesel has a higher density and lower thermal value than B0 [50]. The results of the experiments show that high density cannot compensate for the low thermal value; as a result, by increasing biodiesel content in fuel, to produce the equal power as in pure diesel, it is necessary to use much more fuel per unit time by the engine, or in other words, fuel consumption increases to create the previous power [50]. In addition to these parameters, viscosity, injection pressure, and atomization ratio also have large effects on BSFC [48, 52]. The highest increase in specific brake fuel consumption is related to B100 fuel, which increases fuel consumption by 69.45 % compared to diesel. Also, the greatest reduction in BSFC is related to B20 and B50 fuels, for which due to the high biodiesel content, the braking power is improved and the low thermal value of biodiesel is compensated [47, 53]. In this way, the consumption of special fuel by 2 % is reduced compared to pure diesel and this issue is very important in terms of optimal fuel consumption. Labeckas and Slavinskas claimed that BSFC for biodiesel compounds was higher than B0 and they reported that this increase could result from the thermal value of rapeseed oil, which is about 12.5 % lower than that of diesel [51].

$$y = 17.359X^2 - 57.958X + 300.79 \tag{15}$$

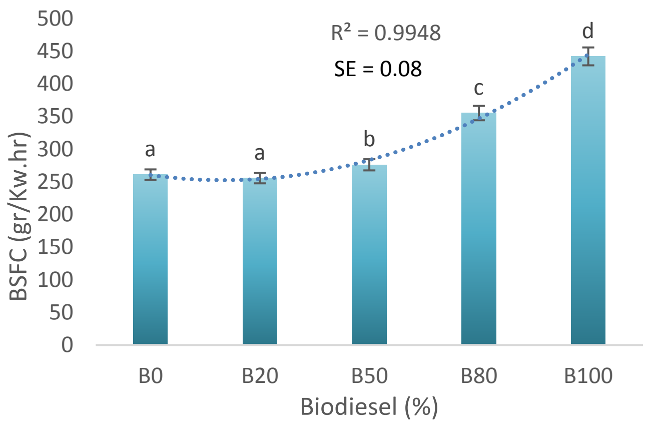

Figure 6. The effect of increasing biodiesel on BSFC

4.7. Brake thermal efficiency

The braking thermal efficiency of a diesel engine is the efficiency in which the chemical energy of the fuel is converted into useful work [54]. The braking thermal efficiency values of diesel fuels B0, B20, B50, B80 and B100 are shown in Figure 7 with the determination coefficient (R^2=0.8871) and standard error (SE=0.773479). Changes in braking thermal efficiency concerning different percentages of biodiesel are a quadratic function that occurs at point B20 with the best braking heat efficiency of the engine at full load and also with minimal braking thermal efficiency at point B100 (Equation 7). Braking thermal efficiency is inversely related to braking specific fuel consumption and fuel thermal value. Thus, the main reason for the reduction in the braking thermal efficiency of B100 fuel compared to other fuel mixtures is higher BSFC and lower HLHV of biodiesel. The results indicated that the BTE of the engine for B20 and B50 fuels is 21.21 % and 7.7 % higher than that for B0, respectively. According to some researchers, the improvement of brake thermal efficiency for these fuels results from more efficient combustion and increased lubrication of these fuel compounds compared to diesel [47, 53]. Shirneshan et al. reported in a study that for all fuel mixtures, upon increasing load, the braking heat efficiency increased due to the reduction of heat loss and the increase in power generated with increasing load [49]. Buyukkaya also tested rapeseed biodiesel compounds with diesel in the engine and concluded that BTE increased with an increase in the amount of biodiesel in the fuel composition, and the probable reason for the increase in BTE biodiesel at full load was its lubrication and the greater amount of oxygen [37].

$$Y = -1.706X^2 + 7.1287X + 23.162 \tag{16}$$

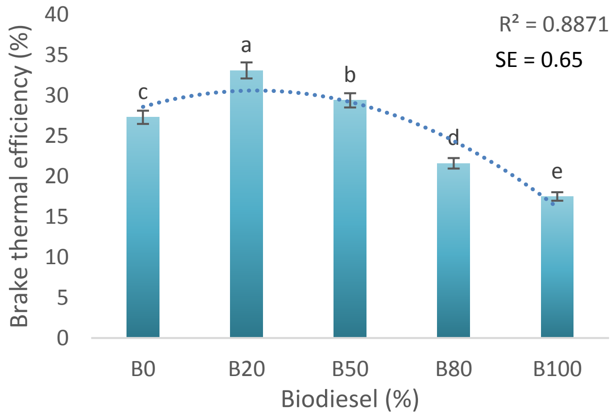

Figure 7. The effect of increasing biodiesel on braking thermal efficiency

4.8. Exhaust gas temperature

Figure 8 indicates the exhaust temperature changes for pure diesel fuel (B0), mixtures of diesel and biodiesel fuel, and pure biodiesel fuel (B100) with the determination coefficient (R^2=0.994) and standard error (SE=11.99893). As biodiesel content in fuel increases, the exhaust gas temperature decreases so that the highest exhaust gas temperature is related to diesel fuel and the lowest temperature is related to B100. Upon increasing biodiesel content, the pressure of the cylinder decreases and as a result, the exhaust gas temperature decreases. The exhaust gas temperature changes with the change in the combustion time delay. Long delays cause combustion delays and as a result, the temperature of the exhaust gases increases [55]. Also, a lower cetane number prolongs the time delay. For this reason, the exhaust gas temperature for B0 fuel is higher than other biodiesel fuel compounds due to its lower cetane number. Aydin and Binder reported that the highest exhaust gas temperatures were observed at 2500 rpm and full load for diesel fuel, which reached 469 °C, while the corresponding values for B20 were 395 °C under the same conditions [44].

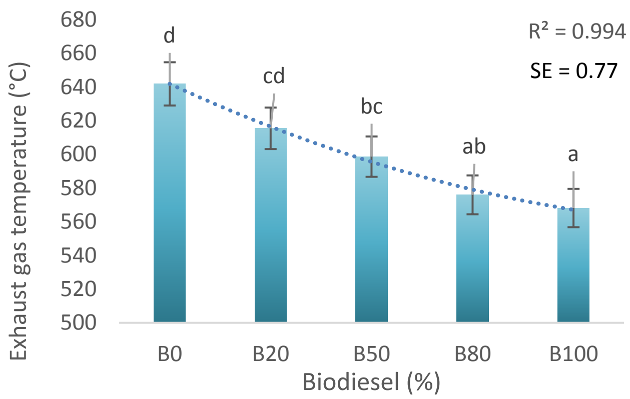

Figure 8. Effect of increasing biodiesel on exhaust gases

4.9. Comparison between the proposed combinations of fuels and pure diesel fuel

To select the most suitable fuel combination from 5 combinations (B0, B20, B50, B80 and B100), a multi-criteria decision method (TOPSIS) was used. According to the steps mentioned in the TOPSIS method, the decision matrix (Table 5), the scaleless matrix (Table 6), the normal weight matrix (Table 7), the PIS and NIS values (Table 8), and the distance from the positive and negative ideal solutions (Table 9) were calculated.

The final rankings of the five compared fuel combinations (B0, B20, B50, B80, and B100) in this study are shown in Figure 9. The results show that B50 fuel is better than pure diesel fuel and other listed fuel combinations.

Table 5. Decision-making matrix

Biodiesel blends	Power (kW)	Torque (N.m)	BSFC (g/kWh)	CO % (vol)	NOx (ppm)	BTE % (vol)	EGT (°C)
B0	99.63551	619.7808	260.8026	0.03135	641.294	27.30035	641.749
B20	101.5263	623.2578	255.4732	0.0247	646.5878	33.09792	615.3804
B50	105.5298	646.6796	275.9305	0.019	673.6998	29.39732	598.579
B80	99.64799	602.2808	355.1309	0.019	701.7747	21.6091	575.924
B100	95.95	587.1	441.94	0.0171	734.35	17.5085	568.1

Table 6. The dimensionless decision matrix

Biodiesel blends	Power (kW)	Torque (N.m)	BSFC (g/kWh)	CO % (vol)	NOx (ppm)	BTE % (vol)	EGT (°C)
B0	0.4433	0.4498	0.3579	0.61396	0.4214	0.4628	0.4778
B20	0.4517	0.4523	0.3506	0.4837	0.4249	0.5611	0.4582
B50	0.4695	0.4693	0.3787	0.3720	0.4427	0.4984	0.4457
B80	0.4433	0.4371	0.4874	0.3720	0.4612	0.3663	0.4288
B100	0.4269	0.4261	0.6065	0.3348	0.4826	0.2968	0.4230

Table 7. The weighted dimensionless decision matrix

Biodiesel blends	Power (kW)	Torque (N.m)	BSFC (g/kWh)	CO % (vol)	NOx (ppm)	BTE % (vol)	EGT (°C)
B0	0.0071	0.00751	0.1071	0.1988	0.0109	0.1370	0.0105
B20	0.0072	0.0075	0.1049	0.1566	0.0110	0.1661	0.0101
B50	0.0075	0.0078	0.1133	0.1204	0.0114	0.1475	0.0098
B80	0.0071	0.0073	0.1459	0.1204	0.0119	0.1084	0.0094
B100	0.0068	0.0071	0.1816	0.1084	0.0125	0.0878	0.0093

Table 8. PIS and NIS values for each dependent variable of five fuel types

	Power (kW)	Torque (N.m)	BSFC (g/kWh)	CO % (vol)	NOx (ppm)	BTE % (vol)	EGT (°C)
PIS	0.0075	0.0078	0.1049	0.1204	0.0109	0.1661	0.0094
NIS	0.0071	0.0073	0.1459	0.1988	0.0119	0.1084	0.0105

Table 9. Distance from the positive and negative ideal solutions

Biodiesel blends	D+	D-
B0	0.0835	0.0481
B20	0.0361	0.0823
B50	0.0203	0.0933
B80	0.0707	0.0783
B100	0.1101	0.0993

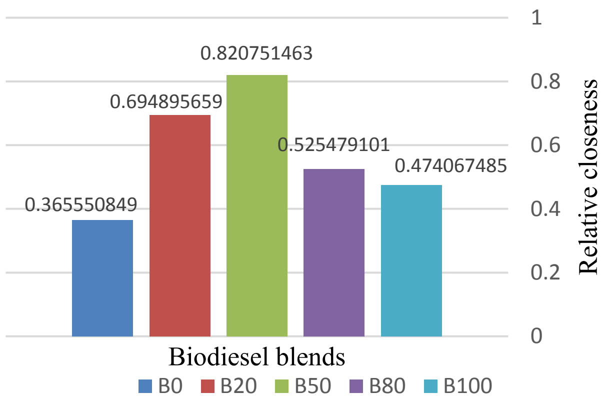

Figure 9. Final ranking of five fuel combinations (B0, B20, B50, B80 and B100)

5. CONCLUSIONS

Despite many types of research in the field of performance parameters and pollution of biodiesel fuel combustion engine, no research has been done so far on the parameters of biodiesel engine of safflower oil with transesterification reaction with the help of hydrodynamic cavitation reactor. According to the experiments conducted in this study, the efficiency of biodiesel produced by a hydrodynamic cavitation reactor was higher than that by conventional and ultrasonic reactors. After biodiesel production, performance characteristics and pollution of different percentages in combination with diesel fuel in the diesel generator engine were studied at the laboratory. The results showed that upon increasing the percentage of biodiesel in the fuel composition, the emission of nitrogen oxides increased due to the high combustion temperature and the emission of carbon monoxide decreased due to the high oxygen content of biodiesel compared to diesel fuel. Following an increase in the volume percentage of biodiesel to 50 % in the combination of fuel, braking power and braking torque increased and, then, decreased due to high fuel consumption and the presence of oxygen content in biodiesel. With the increase in the percentage of biodiesel fuel in fuel mixtures, the consumption of special brake fuels had an upward trend due to the high density and low calorific value of biodiesel. Also, braking thermal efficiency was inversely related to braking specific fuel consumption and fuel calorific value. Exhaust gas temperature decreased by increasing the percentage of biodiesel in the fuel mixture due to the reduction of cylinder pressure and ignition time delay. By using TOPSIS, the comparison between the proposed fuel compositions and the pure diesel fuel demonstrated that the fuel mixtures containing 20 % and 50 % biodiesel in terms of performance characteristics and pollution could be identified as potentially confirmed alternatives for use in diesel generators.

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