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Predicting Performance Characteristics of an Engine Fueled by Algal Biodiesel-Diesel using Response Surface Methodology

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Abstract

The effect of biodiesel percentage in biodiesel-diesel blends on the engine under different engine operation conditions must be predicted to achieve a high performance. The goal of the present paper was to model brake power, brake torque, thermal efficiency, and specific fuel consumption of a diesel engine fueled by algal biodiesel-diesel blends. The response surface methodology was successfully applied to model the performance indicators of biodiesel-diesel fueled OM 314 diesel engine at various engine loads and rotational speeds. Brake power, torque, and thermal efficiency increased by increasing the engine load. Increasing the engine rotational speed caused increase in brake power, whereas the highest brake torque and thermal efficiency was obtained in medium engine rotational speed. Increase of biodiesel percentage caused decrease in. Biodiesel had negative effects, but it had lower effects than engine load and rotational speed on the change of the engine performance indicators. Brake specific fuel consumption decreased by increasing load but it was lowest in medium rotational speeds. A quadratic model was suitably fitted to predict the effects of input-output variables with a statistical significance of 1% probability level. The coefficient of determinations for prediction of the engine brake power, brake torque, thermal efficiency, and brake specific fuel consumption were 97.63, 99.74, 97.41, and 95.72%, respectively. The result of the present work is useful to find a biodiesel percentage and engine load and rotational speed to achieve a higher performance of the engine.

Keywords: *Bio-power, Thermal efficiency, Power, Torque, Fuel consumption.*

1. Introduction

Renewable energy sources have attracted great attentions to be used as engine fuels [1-3] due to decrease environmental impacts and consumption of natural resources, and consequently, move in the sustainable production path [4]. Biodiesel is one of the renewable energy sources that is used in diesel engines due to different benefits [5-7].

Biodiesel as an oxygenated fuel is produced by converting triglycerides of animal fats or vegetable oils into esters during transesterification [8]. This fuel has properties similar to diesel fuel, so that it can be used instead in diesel engines without or with minimal modifications to the engines [9-11]. It decreases the equivalence ratio and engine temperature, and increases the exhaust oxygen fraction. As an environmentally friendly fuel, it can cause reducing exhausting emissions such as carbon monoxide (CO) and particulate matter (PM) [11-13]. Oxygen molecules in the composition of biodiesel can improve combustion efficiency, whereas slightly increase specific fuel consumption in biodiesel fueled engines [14]. The researchers have proven that specific fuel consumption resulting from the use of biodiesel in diesel engines is higher, mainly because of the relatively lower heating value, and higher density of biodiesel [15-17]. It was shown that the average BSFC obtained from B10, B20, B30, B40, and B50 at different engine rotational speeds is 4, 0.8, 0.6, -2.2, and 1.4% more than that of pure diesel, respectively [18]. Biodiesel decreased engine power and torque of diesel engines [17, 19]. The effects of B10, B30, and B50 on the performance of an in-line vertical six-cylinder diesel engine were studied [20], and showed that biodiesel increased the specific fuel consumption by 2.1-9.0%, whereas decreased the brake thermal efficiency, the brake power, and brake torque by

(0.6-5.2%), (1.9-8.4%), and (1.6-6.7%), respectively. Biodiesels are mono-alkyl esters, have the same properties as fossil fuel diesel, but contain approximately 10% oxygen (weight basis). Biodiesel derived from animal fat and vegetable oil (specifically canola, safflower, and waste vegetable oils) does not improve specific fuel consumption, but vegetable-based biodiesels have better results than animal fat-based biodiesel [19]. These research works show different desirable and undesirable effects of biodiesel on the engine emissions and performance characteristics. This fact emphasizes on the prediction of the engine characteristics. Artificial bee colony algorithm was applied to model the biodiesel behavior in an engine [21]. Statistical modeling has been used to analysis the effect of the biodiesel percentage to minimize harmful exhaust emissions [21-23]. The response surface methodology (RSM) is one of the experimental design methods that is used for the prediction goals that has been applied in the present research work.

The present study aims to predict the performance characteristics of diesel engine under various biodiesel percentage and engine loads and rotational speeds by RMS modeling. The effects of engine loads and engine rotational speeds are modeled using the method. The effects of biodiesel extracted from different sources such as linseed [24] soybean [25], crambe [26], tobacco seed [27], palm [28], sunflower [29], poppy seed [17], eucalyptus [30], jatropha [31], curry leaf [32], and animal fat [33] have been evaluated on diesel engines. The novelty of the study is to develop predictive models for diesel engine performance under the effects of algal biodiesel using RMS. By applying RSM, different engine performance indicators such as brake thermal efficiency (BTE), brake power (BP), brake torque (BT), and brake specific fuel consumption (BSFC) are modeled to predict them based on biodiesel percentage, engine load, and engine rotational speed.

2. Materials and Methods

The present research work was conducted in different steps (Figure 1) to investigate and model the effects of alga biodiesel, engine load, and engine rotational speed on the engine performance.

The test setup to determine the BTE, BP, BT, and BSFC was an OM 314 diesel engine, a dynamometer, a dynamometer control panel, a display screen attached to the dynamometer control panel, and a fueling system. The engine was made by the Idem Company, Tabriz, Iran (Figure 2). It was a four-stroke, four-cylinder, direct injection engine with maximum power, torque and rotational speed of 81 kW (at 2800 rpm), 340 Nm (at 1800 rpm), and 2800 rpm, respectively.

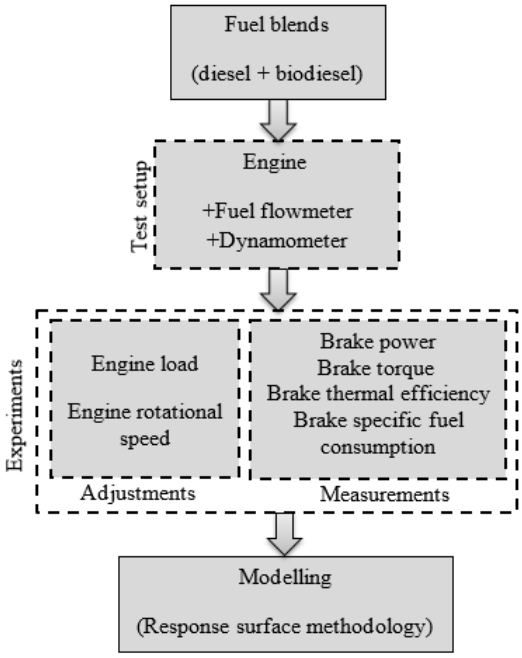

Figure 1. Different steps of the investigation.

To control the rotational speed and measure the brake torque value, a flow-character (ferromagnetic) dynamometer (model E400) was applied. The measuring error of the dynamometer for both brake torque and rotational speed was 1%.

Figure 2. The tested engine OM 314 engine.

Chlamydomonas, a special algae genus with fast growth and high fat content, was used to produce biodiesel. This type of algae needs a simple and cheap environment to grow. The fuel obtained from this type of algae has physicochemical properties very similar to fossil diesel fuel. It was crushed and dried at 80 °C for 20 minutes. About 20 mL of hexane and ether solution was added to the dried algae for a better extraction of algae oil. The extracted biomass was left undisturbed for 24 h to settle. After that, a rotary evaporator was used to separate the hexane and ether solutions. 0.25 g of NaOH catalyst and 24 mL of methanol were mixed together and stirred for 20 minutes, and then injected into the resulting pure algal oil in a conical flask. The algal oil is converted into biodiesel by direct hydrogenation or transesterification process [34-35]. The properties of the studied fuels were determined by the Alborz Tadbirkaran Co., Iran (Table 1).

Table 1. Physicochemical properties of the used diesel and biodiesel fuels.

Fuel type	Cetane number	LHV (MJ/kg)	Density at 15 °C (kg/m3)	Viscosity at 40 °C (cSt)	Pour point (°C)	Flash point (°C)	Sulfur content (%, mass)
Diesel	52.20	42.72	837.00	2.50	-9.00	65.00	0.60
Biodiesel	56.20	41.20	881.00	5.20	2.00	158.00	0.02
B79.73	55.40	41.50	872.00	4.60	-0.20	140.00	0.14
B50	54.20	42.00	859.00	3.80	-3.50	111.00	0.31
B20.26	53.00	42.40	846.00	3.00	-7.00	84.00	0.49

The experiments were conducted in the form of a short-term test with the aim of measuring engine performance parameters under the effects of different mixtures of diesel and biodiesel fuels. The controlled variables were the load applied by the dynamometer to the engine, engine rotational speed, and fuel (various diesel-biodiesel blends). All tests were performed under standard conditions without any technical and structural change on the engine. In each test, firstly, the engine worked on the spot state with the considered fuel blend for 15 minutes to reach a normal and stable condition. Then the engine load and rotational speed were controlled by the dynamometer control panel according to the test table (Table 2), which has been compiled based on the RSM and the Central Composite Design (CCD). The applied torque to the engine was recorded and engine brake power was calculated. Also the mass rate of fuel consumption was measured in kilograms per hour by the fuel consumption measurement system. The temperature of the outlet and inlet water into the engine as well as the temperature of the exhaust gases and the test cell, and the pressure of the engine lubricant oil were also checked through a computer in the control room of the test center.

Table 2. The considered tests based on CCD at coded and uncoded levels of independent variables.

Test No.	Engine load (%)		Engine rotational speed (rpm)		Biodiesel (%)	
	Uncoded	Coded	Uncoded	Coded	Uncoded	Coded
1	36.22	-1	2435.14	1	79.73	1
2	83.78	1	1364.86	-1	79.73	1
3	60	0	2800	1.68	50	0
4	100	1.682	1900	0	50	0
5	36.22	-1	1364.86	-1	79.73	1
6	60	0	1900	0	50	0
7	83.78	1	1364.86	-1	20.26	-1
8	60	0	1900	0	0	-1.68
9	60	0	1900	0	100	1.68
10	60	0	1900	0	50	0
11	60	0	1900	0	50	0
12	60	0	1900	0	50	0
13	83.78	1	2435.14	1	20.27	1
14	36.22	-1	1364.86	-1	20.27	-1
15	20	-1.682	1900	0	50	0
16	60	0	1900	0	50	0
17	36.22	-1	2435.14	1	20.27	-1
18	83.78	1	2435.14	1	79.73	1
19	60	0	1000	-1.68	50	0
20	60	0	1900	0	50	0

The RSM methodology was used for the prediction of the engine characteristics in the Minitab software environment. At least three levels are needed for each independent variable to model the effects of the variables on the responses. The design of the experiment was based on CCD, as the most widely used design in RSM [36].

Independent variables in this study were different levels of biodiesel-diesel blend, engine rotational speeds, and engine load. The desired responses that were included were BP, BT, BTE, and BSFC. The independent variables were selected based on 0, ±1, and ±α axes. The α parameter is the square of the number of independent variables (2 in the present study). The real independent variables (uncoded levels), and coded levels are showed in Table 3.

Table 3. Coding the levels of the independent variables.

Independent variable	Coded levels				
	1.68	1	0	1	1.68
Biodiesel-diesel ratio	100	80	50	20	0
Engine rotational speed (rpm)	2800	2435	1900	1365	1000
Engine load (%)	100	80	62.5	40	20

3. Results and Discussion

The results of variance analysis have been presented in Table 4. The P-values in all models are less than 0.01, which indicate the ability of the models in predicting the effects of independent (biodiesel percentage, engine load, and engine rotational speed) on the dependent (engine performance indicators) variables with low error (< 1%). The parameters with P-values less than 0.05 in Table 4 have been entered into the models. The positive sign of the coefficients indicates that the dependent and independent variables have a direct relationship, whereas the negative sign shows a reverse relationship.

The constant coefficient and lack of fit values were calculated for the models. As listed in Table 4, the model constant coefficient in predicting BTE, BP, BT, and BSFC are 35.149, 43.718, 197.93, and 237.99, respectively. The lack of fit values for predicting the BTE, BP, BT, and BSFC indicators were 0.18, 0.12, 0.21, and 0.26, respectively. These values show the suitability of the models in predicting the dependent variables.

Table 4. Variance analysis of predictive models, model parameters, and coefficients.

Term		Power (kW)			Specific fuel consumption (g/kW.h)			Thermal efficiency (%)			Torque (N.m)		
	DF	P-Value	F- Value	Coefficient	P-Value	F- Value	Coefficient	P-Value	F- Value	Coefficient	P-Value	F- Value	Coefficient
Model	1	0.00	2093.7		0.00	38.3		0.00	64.5		0.00	668.5	
Linear	3	0.00	4692.8		0.00	70.4		0.00	114.6		0.00	1504.5	
Speed (rpm)	1	0.00	3655.4	28.9	0.00	49.2	49.38	0.00	33.8	-4.6	0.00	68.0	-32.5
Load (%)	1	0.00	10338.9	48.6	0.00	99.4	-70.17	0.00	144.0	9.4	0.00	4398.8	260.9
Biodiesel (%)	1	0.00	84.2	-4.9	0.00	62.7	55.75	0.01	165.8	-10.1	0.00	46.4	-26.8
Square	3	0.00	113.8		0.00	10.2		0.00	33.6		0.00	50.5	
Speed × Speed	1	0.00		-13.8	0.00	13.7	42.28	0.00	72.9	-10.9	0.00	135.4	-74.9
Load × Load	1	0.00	51.9	-5.6	0.01	10.6	37.52	0.00	35.5	-7.7	0.00	25.7	-32.7
Biodiesel × Biodiesel	1	0.014	8.2	-2.2	0.04	5.4	-26.7	0.03	6.5	-3.3	0.045	4.9	-14.4
Interaction	1	0.00	236.5		0.00	26.3		0.03	6.6		0.00	14.6	
Speed × Load	1	0.00	236.5		0.00	26.3	-79.3	0.03	6.6	4.43	0.002	14.6	-33.0
Constant	43.7				238.0			35.2			197.9		
Lack of fit	0.18				0.26			0.21			0.12		

3.1. Brake power

The multivariable predictive model for break power indicator under the effects of biodiesel percentage, engine load, and engine rotational speed has been shown as equation (1). The values of coefficient determination (R^2) and adjusted R^2 for the predictive model of engine brake power were 97.63 and 96.71 %, respectively. The high values of the coefficient determinations show a high correlation between the measured and predicted engine power. It also shows the high ability of the model to describe almost 98% of the total BP variation in the tested conditions, and can be used to find the independent variables, i.e. biodiesel percentage, engine load, and engine rotational speed to achieve a better performance of the engine.

$$\mathbf{BP = -33.64 + 0.03494S + 0.3925L + 0.0010B - 0.000009S^2 - 0.001761L^2 - 0.000449B^2 + 0.000224SL} \quad (1)$$

BP: Engine brake power (kW)
B: Share of biodiesel on the blends (%)
S: Rotational speed of the engine (rpm)
L: Exerted load on the engine (%)

The surface and contour plots of BP under the effects of engine load and rotational speed have been presented in figure 3. This figure shows the relationship between independent variables of engine load and rotational speed and dependent variable of BP, based on the predictive model for $B_{50}D_{50}$ (mixture of biodiesel and diesel with equal percentage). According to figure 3, BP increased by increasing load of engine for all fuel blends. The reason for this trend is the increasing of the combustion temperature by increase in engine load, and subsequently, improving the combustion process. As engine rotational speed increases, BP increased somewhat at low and medium loads, but remains constant at high speeds due to cylinder filling. Improper engine rotational speed and load reduces combustion quality and as a result reduces the BP. At high engine loads, the problem is partially solved by increasing the engine rotational speed, which increases the combustion temperature and improves the air-fuel ratio [37-38].

Figure 3 also shows the simultaneous effects of biodiesel and rotational speed on BP at full engine load. BP decreases slightly with the increase of biodiesel fraction in the fuel composition. In similar studies, BP reductions of about 1.6–6.7% [20] and 5-10 % [39] have been reported, mainly due to the low calorific value and high viscosity of biodiesel. The low calorific value and high viscosity of biodiesel also decreases and increases the calorific value and viscosity of the fuel mixture, respectively, thus causing disturbance in fuel atomization during fuel injection. In general, these two factors prevent the creation of a proper combustion process and, as a result, reduce the BP [40].

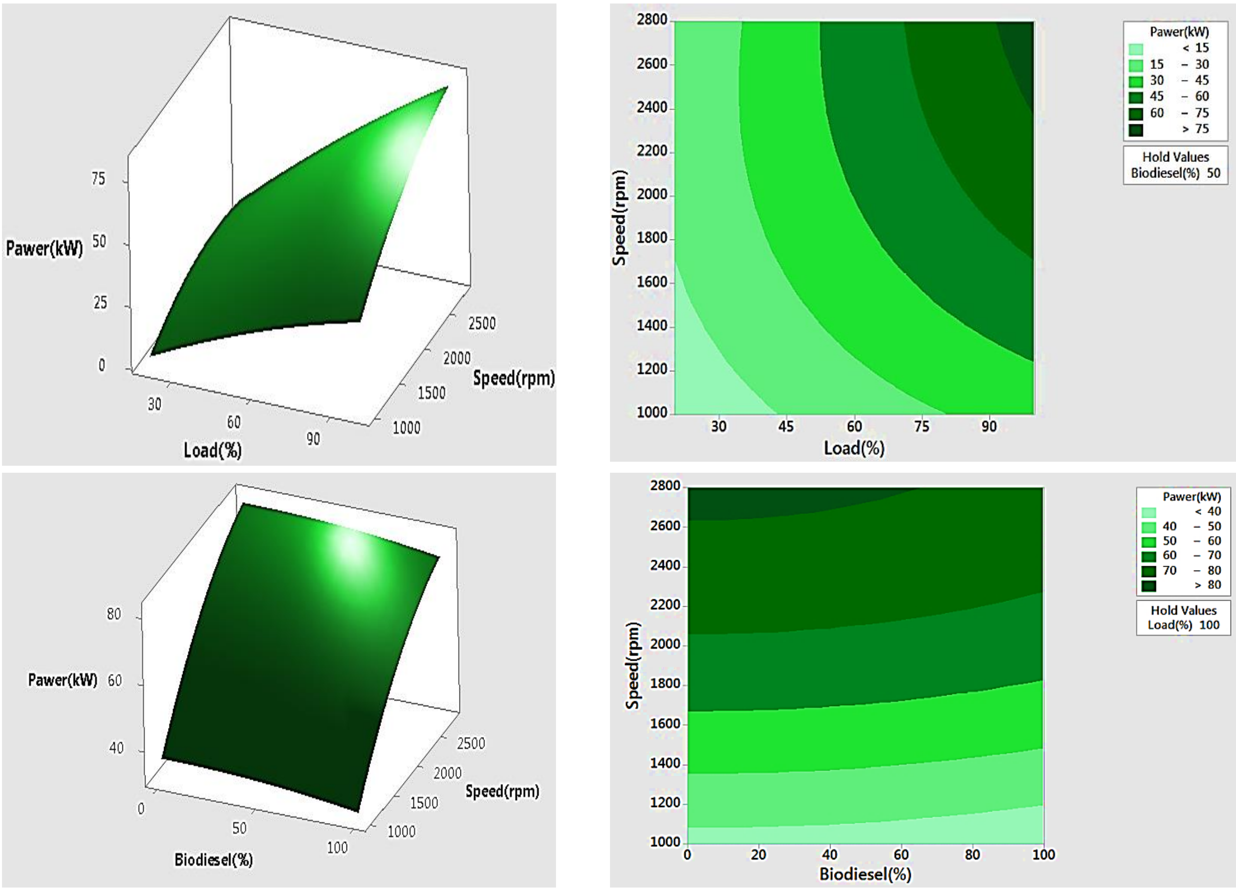

Figure 3. The effects of engine load and rotational speed on engine brake power (kW) for B50D50 blended fuel (top) and effects of biodiesel and engine rotational speed on engine brake power (kW) at full engine load (bottom).

In general, due to the favorable combustion process, mainly due to the presence of oxygen molecules in the biodiesel composition, the low percentage of biodiesel in the fuel mixture results the BP similar to that of diesel fuel. When the proportion of biodiesel in the fuel mixture increases, the high density, high viscosity, and low calorific value of biodiesel overcome the advantages of the high oxygen content of biodiesel and gradually reduce the BP.

3.2. Brake torque

Equation (2) is the developed model to predict engine brake torque. The R^2 and adjusted R^2 of the model were 99.74 and 99.59, respectively. These results indicate a very high correlation between measured and predicted BT of the diesel engine. Therefore, this model can be reliably used to predict BT based on biodiesel percentage, engine load, and engine rotational speed.

$$\mathbf{T = -213.2 + 0.1852S + 5.357L + 0.020 - 0.000046S^2 - 0.01021L^2 - 0.00288B^2 - 0.000458SL} \quad (2)$$

BT: Engine brake torque (Nm)
B: Share of biodiesel on the blends (%)
S: Rotational speed of the engine (rpm)
L: Exerted load on the engine (%)

Figure 4 depicts the BT changes based on engine loads and rotational speeds when the engine was fueled by $B_{50}D_{50}$ blend. Brake torque increased at higher engine loads because in this conditions the cylinder temperature is higher and therefore the air-fuel mixture is more suitable. The effect of biodiesel and engine rotational speed on BT at full load has been also presented by surface and contour plots in figure 4. BT decreased slightly in all engine conditions when the proportion of biodiesel in the fuel mixture increased. This result is in line with the results of Uyumaz et al. [17] and Simsek and Uslu [19]. The amount of this reduction was reported in a similar study to be 5-10% [39] and 5.2-6% [13]. The most likely explanation is the lower calorific value of biodiesel compared to that of pure diesel fuel [17]. In addition, the higher viscosity and density of biodiesel prevents atomization of the fuel, thereby reducing BT [41].

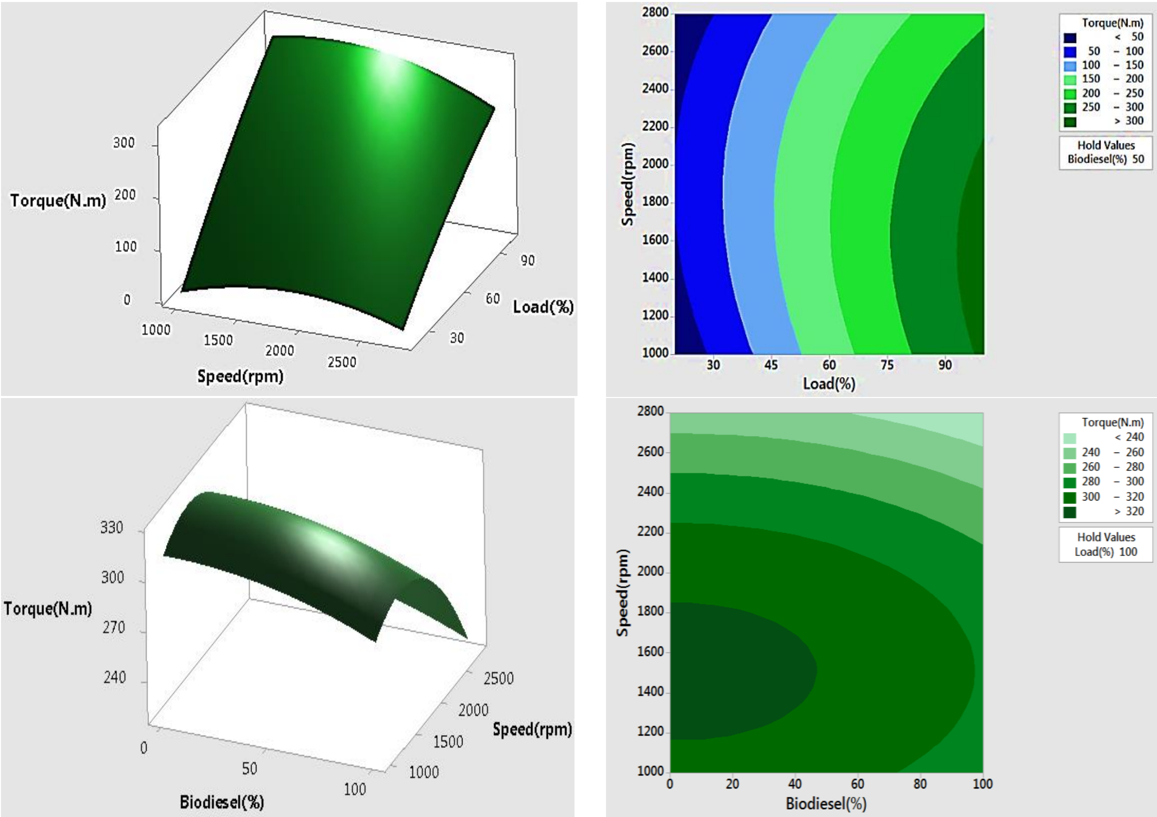

Figure 4. The effects of engine load and rotational speed on engine brake torque (Nm) for B50D50 blended fuel (top) and the effects of biodiesel and engine rotational speed on engine brake torque (Nm) at full engine load (bottom).

3.3. Thermal efficiency

The developed model for predicting the thermal efficiency (Equation (3)) has obtained relatively acceptable values for R^2 and adjusted R^2 as 97.41 and 95.9%, respectively. This model can predict BTE of the engine based on independent variables of biodiesel percentage, engine load, and engine rotational speed.

$$\mathbf{BTE = 10.24 + 0.01953S + 0.2883L - 0.0355B - 0.000007S^2 - 0.002394L^2 - 0.000657B^2 + 0.000062SL} \quad (3)$$

BTE: Engine brake thermal efficiency (%)
B: Share of biodiesel on the blends (%)
S: Rotational speed of the engine (rpm)
L: Exerted load on the engine (%)

Figure 5 shows the relationship between independent variables of engine load and rotational speed of and BTE of the engine when fueled by $B_{50}D_{50}$ blend. Because there is no interaction between the blended fuels and engine load and rotational speed, the descriptions are the same as that of other tested blended fuels.

Figure 5 shows that BTE increased with increasing engine load. This is mainly due to the increase in fuel-air ratio and combustion temperature [42]. Also with the increase in engine rotation speed, BTE increases first and then decreases in all tests. Similar results have been obtained in different research works [41, 43]. The decrease in BTE at high rotational speeds is due to the insufficient time to fill the cylinder and the decrease in volumetric efficiency of the engine. Also the relationship between BTE and the share of biodiesel in fuel blend at full engine load and rotational speed of 2800 rpm has been plotted in figure 5. As shown in this figure, BTE decreased by increasing the biodiesel share in the fuel blends. As reported by Fatt et al [20] biodiesel reduced BTE by 1.9-8.4%. The physicochemical properties of biodiesel such as high viscosity and low heating value can reduce BTE [44].

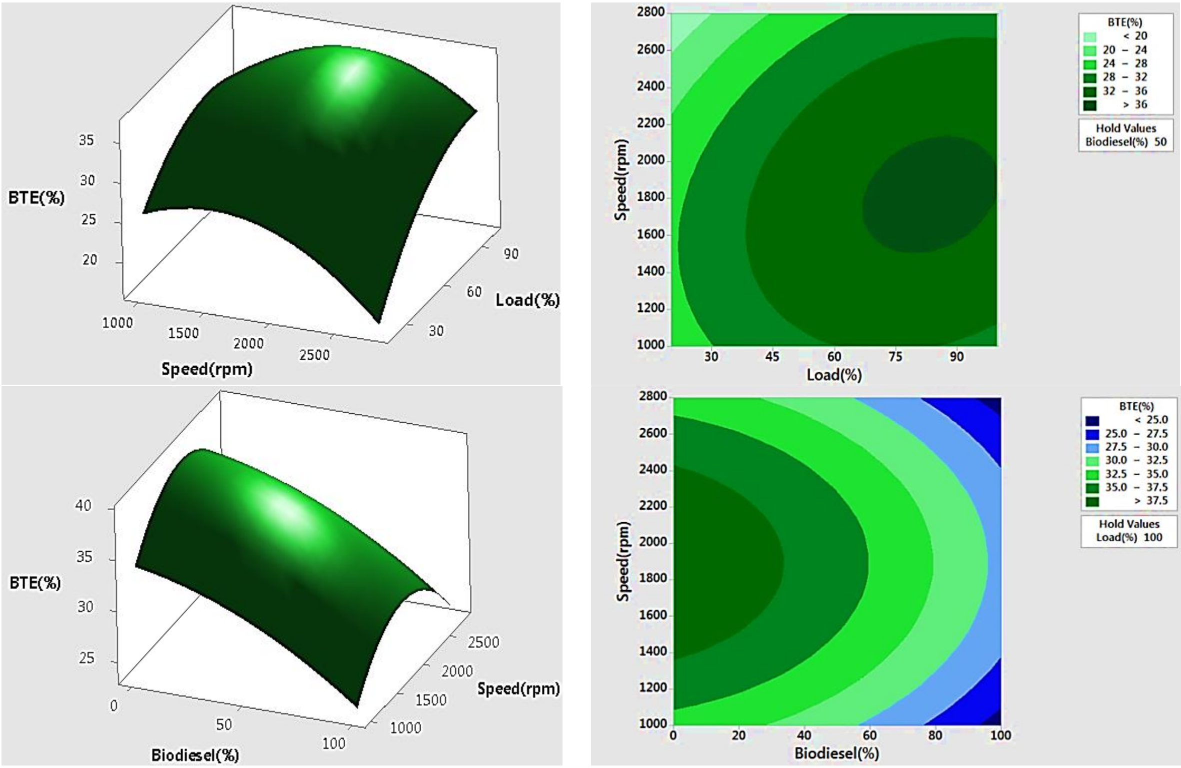

Figure 5. The effects of engine load and rotational speed on engine thermal efficiency (%) for B50D50 fuel blend (top) and the effects of biodiesel and engine rotational speed on engine thermal efficiency (%) at full engine load (bottom).

3.4. Brake specific fuel consumption (BSFC)

The predictive multivariable model for brake specific fuel consumption has been obtained as equation (4). The values of R^2 and adjusted R^2 of the model were 95.72% and 93.22%, respectively. These results show that the obtained model has high ability to predict and interpret 95.72% of all changes in BSFC in the test conditions based on the studied dependent variables.

$$\mathbf{BSFC = 208.1 - 0.0056S - 0.191L + 1.092B + 0.000026S^2 + 0.01172L^2 - 0.00534B^2 - 0.001102SL} \quad (4)$$

BSFC: Brake specific fuel consumption (g/kWh)
B: Share of biodiesel on the blends (%)
S: Rotational speed of the engine (rpm)
L: Exerted load on the engine (%)

Figure 6 shows the relations between BSFC and independent variables of engine load and rotational speed. The BSFC decreased with increasing engine load for all fuel blends tested. This trend is more intense at lower engine speeds. This is mainly due to increased cylinder pressure and temperature as the engine load increases and more thermal energy is converted into mechanical work, especially at high loads [45].

As engine rotational speed increased, BSFC reduced at low loads, then decreased at medium loads, and finally increased at high engine loads. The decrease in BSFC at medium rotational speeds of the engine is due to the increase in air-fuel ratio, but its increase at high rotational speeds is due to the decrease in volumetric efficiency [46].

Figure 6 also presents the effects of biodiesel and engine rotational speed on BSFC at full engine load. Due to the low calorific value of biodiesel, BSFC increases with increasing percentage of biodiesel in the fuel mix. This result is in agree with the result of a research conducted by [17, 46]. Another reason is the viscosity and density of biodiesel, which is higher than that of diesel fuel [44]. In a similar study, BSFC increased by 2.1-9.0% using cooking waste biodiesel [13].

In the previous research works, the determination coefficients (R^2) in modeling of engine break power, thermal efficiency, and specific fuel consumption under the effects of rapeseed biodiesel were obtained as 98.86, 96.52, and 96.34%, respectively, using RSM [23]. The accuracies of the models developed by Khoobbakht et al. [47] to predict engine emissions under the effects of biodiesel were in the range of 90.85-98.69%. Sharma et al. [48] achieved 92.92-99.60% accuracy in prediction of the performance of a biodiesel fueled engine using artificial neural network method. The predictive results of the present study are acceptable in comparison with those of the previous research works. The advantage of the ANN method in comparison with the statistical data analysis methods is higher reliability in data extrapolation, but RSM is better than ANN in point of lower required number of experimental tests.

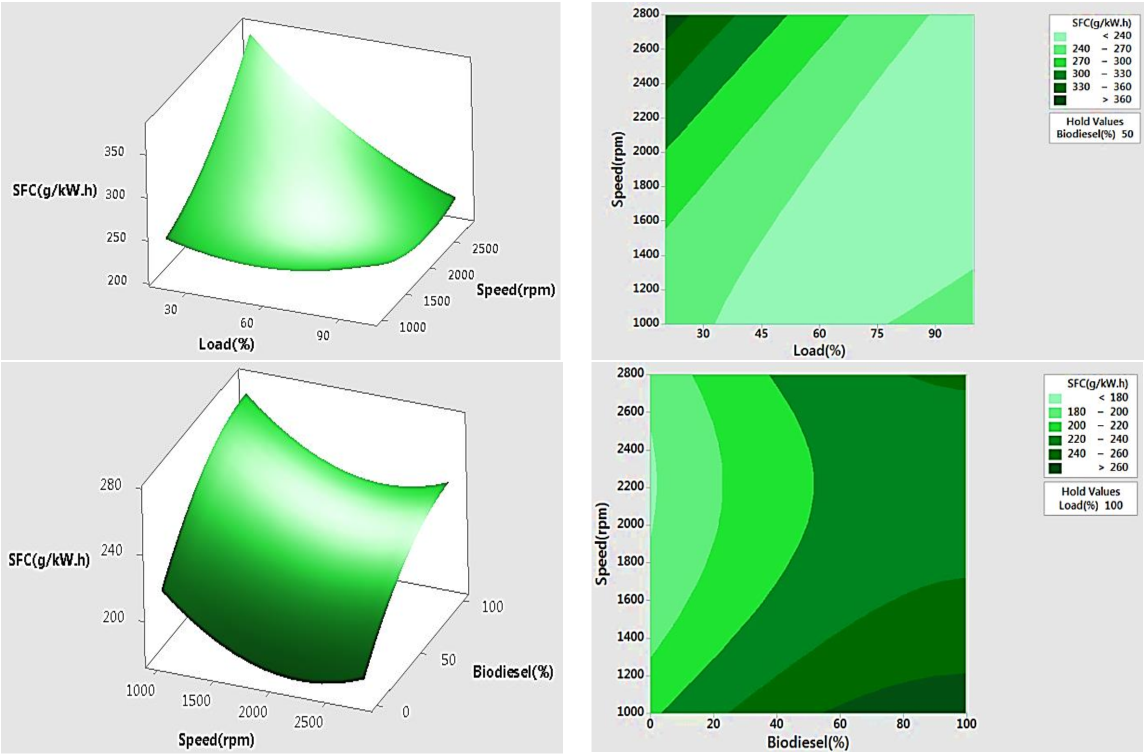

Figure 6. The effects of engine load and rotational speed on brake specific fuel consumption (g/kW.h) for B50D50 blended fuel (top) and the effects of biodiesel and engine rotational speed on brake specific fuel consumption (g/kW.h) at full engine load (bottom).

4. Conclusions

Engine performance indicators under the use of different blends of algal biodiesel-diesel fuel, engine load, and engine rotational speed were measured and modeled using the response surface methodology. The obtained models for all performance indicators were statistically significant at the 1% probability level. The results showed that brake power for all studied fuel blends increased with increasing engine load and engine rotational speed. The effect of engine load and engine rotational speed on BP is greater than that of the amount of biodiesel in the fuel composition. As the engine load increased, the braking torque and thermal efficiency increased. As engine rotation speed increased, BT and BTE initially increased and then decreased. At lower biodiesel percentages in the fuel blend, higher BP, BT, and BTE were obtained. The results for BSFC were opposite with those of other studied indicators. The modeling results indicated that response surface method can successfully predict dependent variables of brake power, torque, thermal efficiency, and specific fuel consumption based on biodiesel percentage and engine load and rotational speed with high accuracy (95.72-99.74%). In the future research works and applications, the methodology presented in the manuscript can be used for predicting engine performance, while decreasing the test numbers, and consequently reducing the experimental time and cost.

5. Abbreviations

B	Biodiesel
BD	Biodiesel-Diesel
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BT	Brake Torque
BTE	Brake Thermal Efficiency
CO	Carbon monoxide
D	Diesel fuel
L	Engine load
PM	Particulate matter
RSM	Response surface methodology
S	Engine rotational speed

6. Acknowledgements

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