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Optimization of Performance and Emissions of a Diesel Engine Fuelled with Rubber Seed- Palm Biodiesel Blends using Response Surface Method

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ABSTRACT— ***The effects of engine speed and load, and fuel blend ratio on the emissions and performance of an IDI (indirect injection) diesel engine were investigated. A 50:50 vol. blend of rubber seed and palm oils was used for the biodiesel production to reduce costs and enhance properties. Oil acid was reduced from 33.4 to 1.42 mg KOH/g oil by esterification followed by a transesterification in a hydrodynamic cavitation reactor. Blends of 0- 40 vol. % biodiesel to a diesel with 10% increments were prepared. Statistical tool, BBD (Box-Behnken design) based on a RSM (response surface methodology) was used to assess the combined effects of variables on parameters such as BT (torque), BP (power), BSFC (brake specific fuel consumption), BTE (brake thermal efficiency), CO, CO2, NOx, EGT (exhaust gas temperature) and O2. The engine load was found to be the most influential parameter compared to the engine speed and fuel blend. The engine speed was found to have a strong effect on performance and emissions except on BT and O2. The fuel blend effect was less significant except for BSFC, BTE, CO and CO2. On average biodiesel blends showed lower BT (0.97- 1.6%), BP (0.94- 1.4%), BTE (0.76-1.5%) and CO (0.93-6.7%) but higher BSFC (0.93- 1.7%), CO2 (0.95- 1.1%), NOx (0.97- 1.2%), EGT (1.1- 1.3%) and O2 (0.3- 1.2%) compared to diesel fuel. An optimum desirability value of 0.96 was achieved with fuel blend of 18 % (biodiesel to diesel), engine speed of 2320 rpm and engine load of 82% for the tested IDI engine.***

Keywords— Response surface methodology, hydrodynamic cavitation reactor, biodiesel, performance, emissions

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1. INTRODUCTION

The Fossil fuel depletion and carbon dioxide emissions are increasing due to the accelerated urbanization and industrialization [1]. Biodiesel consists of mono alkyl esters of fatty acids produced by chemical conversion of vegetable oils or animal fats [2]. The use of biodiesel fuels in diesel engines has both environmental and economic advantages such as reduction in emissions, local availability of raw material and improved energy security. Currently, most of the biodiesel productions come from edible sources such as soybean, palm and sunflower oils. However, due to land limitation, food verses fuel issues and energy policies, their industrial expansion has been limited [3]. Although biodiesel productions from these sources are inevitable for their availability and large production levels, reducing their amounts using non- edible sources will relieve them for other uses. Blending edible/non-edible oils is a solution that will have significant contribution towards the advancement of the industry. Jatropha-palm oil, Jatropha- soapnut and Mahua-simarouba oil blends have been investigated [4-8] and observed to be good potential sources for biodiesel productions. In Malaysia, there are 1,229,940 hectares of rubber plantation according to the association of NRPC (Natural Rubber Producing Countries) and the projected annual production is estimated to be 1.2 million metric ton per year [9]. Each tree yields 1.3 kg on average twice a year. The kernel has an average oil of 40- 50 wt. % and can be used for biodiesel synthesis [10]. Comprehensive literature on the rubber seed oil based biodiesel production process is available in [11-15]. Recently, the palm oil based biodiesel usages in diesel engines was studied by many researchers [16, 17]. Liaquat et al. [18] investigated the PB20 effect during an endurance test. CO and THC were found to be lower by 11% and 11.71%, respectively whereas BSFC and NOx were higher by 3.88% and 3.31%, respectively compared to their diesel counterparts. Satyanarayana and Muraleedharan [19] studied the rubber seed oil biodiesel in a single cylinder diesel engine at difference loads and a constant speed of 1500 rpm. They reported less torque and power, 4.95% lower BTE, higher BSFC, 0.037% lower CO, lower THC and higher NOx compared to diesel fuel. Raheman et al. [7] investigated the performance and emissions of the Mahua-simarouba oil mixture biodiesel using a single cylinder diesel engine. The results showed higher BSFC and NOx while BTE, CO and THC were lower compared to diesel fuel. Michael et al. [20] investigated the soybean-soapstock biodiesel in a diesel engine and observed a reduction in CO and THC. Due to the slightly chemical composition differences, biodiesel fuel combustion may differ from the actual diesel fuel and results in different emissions and performance. Investigations of different oils blended biodiesels in a diesel engine in the literature, mostly focused on examining one parameter effect such as the engine speed, engine load, blends ratio, IT (injection timing) or IP (injection pressure) at a time as presented in Supplementary 1. However, the diesel engine combustion process is influenced by the combined effects of all the above mentioned parameters. Therefore, a multi-variation investigation could provide clear knowledge on the combustion behaviour rather than one variable at a time. Multi-variation studies, methods such as DoE (Design of experiments), ANN (artificial neural network) and fuzzy logic are suitable to explore the combination effects of input parameters. DoE is accepted the most effective and economical technique compared to ANN and fuzzy logic. Bhattacharya et al. [21] investigated the effects of load, speed and injection timing on the BSFC, exhaust emissions and noise. BSFC limitation is reported by lower load, noise being limited with higher speed and advance timing, whereas THC and NOx are limited by advance timing. Pandian et al. [22] studied the effects of injection parameters such as nozzle tip protrusion, IP and IT in a twin cylinder diesel engine fuelled with Pongamia biodiesel. They found that advancing the IT from 18° to 30° BTDC (before top dead center) and increasing IP from 150 to 250 bar reduced the THC, CO and smoke emission and increased NOx. Better BTE and lower BSFC were reported at moderated nozzle tip protrusion. Sivaramakrishnan and Ravikumar [23] optimized the operating parameters such as fuel blends and CR (compression ratio) using a single cylinder diesel engine. The results showed that advancing CR reduced the CO and THC while decreasing the fuel blend ratio resulted in better BTE, lower BSFC, NOx, THC and CO. Jagannath and Atul [24] optimized the effect of CR and IP in a single cylinder diesel engine using waste fried oil biodiesel. Increasing CR and IP increased the BTE, EGT and decreased the BSFC. There is a lack of knowledge, in the literature on the optimization of engine emissions and performance of rubber seed and palm oil blend biodiesels. Therefore, new biodiesel fuel with improved properties was developed by blending the rubber seed and palm oil at an equal blend ratio. The RSM method was utilized to investigate the parametric effects on the transesterification process, engine performance and emissions characteristics. Methyl ester at optimized conditions was produced using two-steps, acid esterification and transesterification process in a HC (hydrodynamic cavitation reaction) and thermo physical properties were studied. The individual and combined effects of the engine load and speed, and fuel blend ratio on the emissions and performance of an IDI were examined.

2. MATERIAL AND METHODS

2.1 Material

Rubber seed/palm oil mixture at a blend ratio of 50:50 vol. % was characterized following the AOCS (American Oil Chemistry Society) standard method [39]. Oil blend property values such as acid value, iodine value, free fatty acid, density, viscosity, calorific value, sulfur and nitrogen content were 33.4 mg KOH/g oil, 95.1 mg/I2/g oil, 12%, 914.64 kg/m3, 43.8 cSt at 25°C, 38182 J/g, 0.55 wt.% and 0.41 wt.% respectively.

2.2 Transesterification process optimization

Transesterification is a chemical conversion process in which the triglycerides are converted to fatty acid alkyl esters. An oil blend with acid value of 33.4 mg KOH/g oil was reduced to 1.42 mg KOH/g oil in a pre-treatment process (acid esterification). The treated oil was used in the transesterification process. A three-neck round bottom flask of 250 ml attached to a condenser to avoid alcohol losses was used. Input factors and their ranges were, (-1) low level, (+1) high level and on the axial direction were (-2) low level and (+2) high level as presented in Table 1. The required temperature, mixing time and amount of methanol and catalyst (potassium hydroxide) followed the experimental plan in Supplementary 2. After the specified time, the reaction process was stopped and the product was left for separation gravitationally. Two layers of liquids such as methyl ester upper and glycerol lower were formed after 12 hours and deionized warm water was used to wash the methyl ester. The optimized conditions for 92% conversion yields were reaction temperature and time of 64°C and 2.5 hours, catalyst amount of 1.3 and a methanol to oil ratio of 6:1.

Table 1: Independent variables and levels used for transesterification study

Process parameters	Symbols	Levels				
		-2	-1	0	+1	+2
Alcohol to oil molar ratio	A	4.64	6	8	10	11.36
Catalyst amount (wt. %)	B	0.66	1	1.5	2	2.3
Reaction temperature (°C)	C	38	45	55	65	72
Reaction time (hr)	D	0.32	1	2	3	3.68

2.3 Biodiesel production

Hydrodynamic cavitation reactor (HC) with a 50 L capacity was used for the biodiesel production. The system consisted of a double jacketed glass and air compressor with maximum power of 4 kW to operate the double diaphragm pump as the main device to dissipate the energy in the HC reactor. The previously optimized plate geometry with a 1 mm diameter, 21 holes, 16.5 mm2 total flow area and 65.98 mm perimeter was used [40]. The inlet pressure of two bars was regulated using the main line valve and bypass line. The reaction temperature and its desired level were achieved by circulating liquid glycerine through the jacket surrounding the reactor. A 30 kg of oil mixture per run was pre-treated using previously optimized conditions [41]. The mixture after esterification was transferred to the transesterification process and the above mentioned optimizations were used. The reaction was stopped after the specified time and the product was left for separation gravitationally. After four hours two layers of liquid; methyl ester and glycerol were formed. Deionized warm water at 40°C was used to wash the methyl ester to remove impurities, whereas the methanol and remaining water were removed using the rotary vacuum evaporator. To insure the product was water free, 10 g of anhydrous sodium sulphate was added, shaken for one minute and the product was filtered using a 541 Whatman filter paper. Finally the produced biodiesel was stored for the properties study and engine testing.

2.4 Fuel preparation

The preparation of the fuels and property study were carried out at Universiti Teknologi PETRONAS. Samples of pure fossil diesel fuel, B10, B20, B30 and B40 vol. % of biodiesel to diesel fuel were investigated. The blends were mechanically stirred for 30 minutes at 2500 rpm. The equipment used, and the properties of the methyl ester and blends followed ASTM and EN standard methods as shown in Tables 2 and 3 respectively.

Table 2: Methods and equipment used for biodiesel characterization

Parameters	Methods	Equipment
Density (kg/m3)	ASTM D 5002 and ASTM D4502	DMA 4500M, Anton Paar
Viscosity (mm2/s)	DIN 53015 and DIN 12058	2000 M/ME, Anton Paar, Lovis
Calorific value (MJ/kg)	DIN 51900 and ASTM D 4868	C5000 IKA Werke, Germany
Cetane Number	ASTM D 613	Shatox Octane meter, SX-100K
Oxidation stability (h)	EN 14112 standard	873-CH-9101 Metrohm
Flash Point (°C)	ASTM D 93	CLA 5, Petrotest
Cloud Point (°C)	ASTM D 2500	CPP 5G's
Pour point(°C)	ASTM D 97	CPP 5G's
Clod Filter Plugging Point (°C)	ASTM D 6371	FPP 5G's
Surface tension (Nm)	-	Rame Hart model 260
CHNS (wt. %)	-	Perkin Elmer, Series II CHNS/O 2400

Table 3: Methyl ester and blends properties

Property		Biodiesel	B10	B20	B30	B40	Diesel
Density (kg/m3) at 25°C		872	829.5	832.4	838.1	840.8	825
Viscosity at 40°C (mm2/s)		3.4	3.2	3.25	3.27	3.29	3.21
Calorific value (MJ/kg)		39.5	42.83	42.45	42	41.7	43.2
Cetane Number		51.2	47.4	47.8	48.4	48.61	47
Oxidation stability (h)		8.92	94.1	82.67	76.3	66.72	103.6
Flash Point (°C)		151	80.2	89.12	94.2	102.8	72.4
Cloud Point (°C)		5	-14.6	-12.4	-9.7	-8.01	-17
Pour point(°C)		-1	-28.7	-25.6	-21.8	-19.5	-32
Clod Filter Plugging Point (°C)		0	-	-	-	-	-
Surface tension (Nm)		29.3	27.3	27.52	27.64	27.96	27.08
Perkin Elmer, CHNS, 2400	Carbon (% w/w)	75.38	85.49	84.26	83.6	82.01	86.62
	Hydrogen (% w/w)	11.38	13.01	12.8	12.63	12.42	13.21
	Nitrogen (% w/w)	0.07	0.015	0.023	0.027	0.032	0.01
	Sulfur (%)	0.01	0.144	0.12	0.11	0.1	0.16
	Oxygen (%)	12.77	1.4	2.8	3.9	5.12	0.0

2.5 Engine testing

The experiments were conducted on a multi cylinder, naturally aspirated, water cooled IDI engine (XLD 418D). The specifications and engine testing setup are presented in Table 4 and Figure 1. A Eddy current dynamometer, model SE 150, water cooled, maximum power of 150 kW, maximum torque of 500 Nm and maximum speed of 8000 rpm was used. The engine and the dynamometer were controlled using an ECU (engine control unit) equipped with sensors, logging, thermocouples and data acquisition device. The experiment started with the engine warming up for about 30 minutes using the diesel fuel and the test was conducted at full and part load conditions and various speeds of 1000 to 4000 rpm with 500 rpm intervals. Parameters such as BT, BP, BSFC and fuel flow rate were recorded using a computer and data logger. The engine was flushed with fossil diesel after every fuel changing and run for 20 minutes to insure complete consumption of the pervious sample. The experiment was repeated three times to insure stable reading of performance values. The emissions such as NOx, CO, EGT, O2 and CO2 were measured using VARIO Plus Industrial exhaust gas analyser following the EN 50379-2 standard. The repeated measured data for each blend were averaged prior to using them for analysis and discussion.

Table 4: Engine specifications

Engine	Diesel engine
Model	XLD 418D
Type	4 stroke
Rated BT	110 Nm at 2500 rpm
Rated BP	44 kW at 4800 rpm
Cylinder number	4 in line
Engine design	OHC
Engine cooling	water cooling pressurized circulation
Combustion	IDI, natural aspirated
Bore × stroke	82.5×82 mm
Displacement	1753 cc
Compression ratio	21.5:1

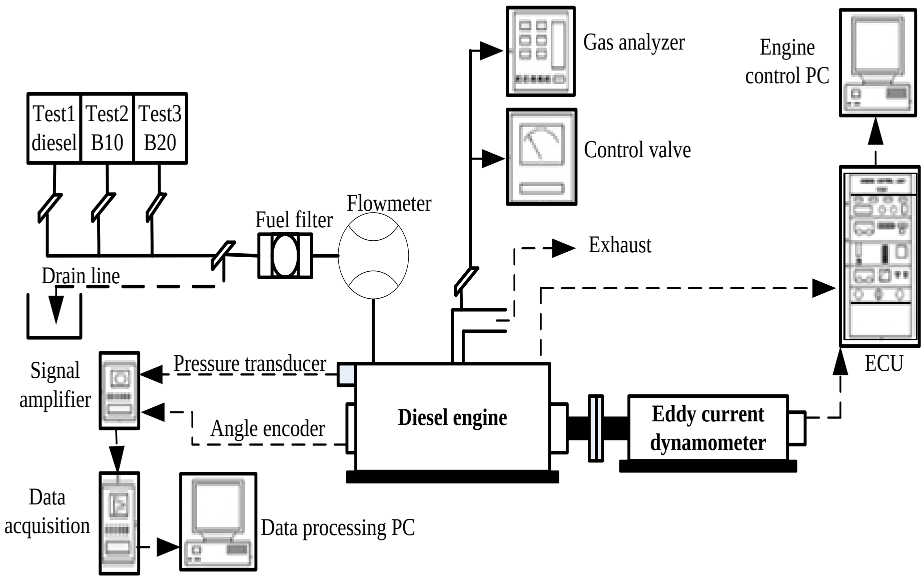


Figure 1: Schematic diagram of engine testing

2.6 Response surface methodology

In complex variables processes, conducting many experiments would be time consuming and expensive. It is essential to have a well-designed experimental plan in order to capture more information from fewer experiments compared to the conventional methods (one factor at a time). RSM is a statistical and mathematical tool useful for analysing, modelling, optimizing and determining the interactions between the variables and responses. The aim is to build models, evaluate the effects of variables and establish the optimum performance conditions by means of experimental design and regression analysis. In the RSM the relationship between the responses and variables is presented by Equation (1).

$$y = f(x_1, x_2, x_3.......x_n) \pm \varepsilon \tag{1}$$

where y is the dependent variable, f is the response function, x_i are the independent variables and ε is the fitting error [42]. In this study, the design involved the selection of variables that influence the emissions and performance of diesel engines such as engine load and speed, and fuel blend ratio. The variables were set at three levels and presented as in Table 5, with five center points and two replication points using Box-Behnken design (BBD) based RSM. The total experimental runs were 34 as shown in Supplementary 3. The experiments were conducted prior to the plan design and the data collected was loaded into the Design Expert version 8.0.6 software. The reason for the selecting of BBD was because of the need for less experimental runs compared to the CCD (Central Composite Design). More so, BBD generates a combination of experiments within the upper and lower limit of input variables, unlike the CCD that generates axial points and usually lies outside the limit range which may be outside the controllable range or safety working limits [43].

Table 5: Factors parameters

Variables	Symbols	Levels		
		Lower	mean	Upper
Blend (vol. %)	A	0	20	40
Speed (rpm)	B	1000	2500	4000
Load (%)	C	40	70	100

2.7 Desirability based optimization study

An optimization study was carried out using the RSM. The responses were transformed to a dimensionless desirability value (d) ranging from 0 to 1. The value of d= 0 suggests that the response is unacceptable, whereas the value of d= 1 suggests that the response is desirable [23]. The goal of each response can be either minimum, maximum, target, in the range and/ or equal depending on the nature of the problem [22]. The desirability value of each goal was calculated using the following Equations (2)- (5) [22]. For minimum goal, di =1 when Yi ≤ Lowi; di = 0 when Yi ≥ Highi ; and

$$d_i = \left[\frac{High_i - Y_i}{High_i - Low_i}\right]^{wt_i} \quad \text{when } Low_i < Y_i < High_i \tag{2}$$

For maximum goal, di = 0 when Yi ≤ Lowi; di =1 when Yi ≥ Highi and

$$d_i = \left[\frac{Y_i - Low_i}{High_i - Low_i}\right]^{wt_i} \quad \text{when } Low_i < Y_i < High_i \tag{3}$$

For target goal di = 0 when Yi < Lowi; Yi > Highi

$$d_i = \left[\frac{Y_i - Low_i}{T_i - Low_i}\right]^{wt1_i} \quad \text{when } Low_i < Y_i < T_i \tag{4}$$

$$d_i = \left[\frac{Y_i - High_i}{T_i - High_i}\right]^{wt2_i} \quad \text{when } T_i < Y_i < High_i \text{ ; and} \tag{5}$$

For a goal within the range d_i = 1 when $Low_i < Y_i < High_i$; and d_i = 0. where i indicates the response, Y is the response value, Low is the lower limit value, High is the higher limit value, T is the target value and wt. is the response weight. The weight value was in the range of 0 to 10. Weight values >1 give more emphasis to the goal, whereas weight values < 1 give less emphasis [22]. At the weight value equals to one, the desirability function varies linearly. In a multi response optimization based desirability approach, multiple responses are combined in a dimensionless overall desirability function, D (0 ≤ D ≤ 1) and calculated using Equation (6).

$$D = \left(\prod_{i=1}^{n} d_i^{ri}\right)^{1/\sum ri} \tag{6}$$

In the overall desirability function (D), each response is assigned an importance (r) with respect to other responses. The importance varies from the least important value (1) indicated by (+) and most important value (5) indicated by (+++++). A high value of D indicates more desirable value and is considered as the optimum solution. The optimum values of factors are determined from the individual desired function (d) that maximizes D [23, 24].

3. RESULTS AND DISSCUSSION

3.1 Effects of catalyst, oil to alcohol ratio, reaction time and temperature on fame yield

The parametric effects such as reaction temperature, time, catalyst and oil to alcohol ratio on FAME conversion based transesterification are presented in Figure 2(a-d). It was observed that by increasing the alcohol to oil ratio and catalyst, the FAME yield decreased as shown in Figures 2(a), 2(b) and 2(c). The reason behind is due to the saponification reaction resulting in poor product separation and high glycerol formation [44]. Also, it was noticed that the first 25-30 minutes of reaction time were enough to achieve the maximum amount of FAME yield, whereas the FAME conversion rate increased as the reaction temperature increased and promoted reaction towards the product side as presented in Figures 2(b) and 2(d) [45]. Junaid et al. [13] claimed that increasing the alcohol amount increases the ester content to a certain limit before it decreases as the alcohol ratio increases, whereas the higher amount of methanol ratio hinders the glycerol separation, hence lowers the FAME yield.

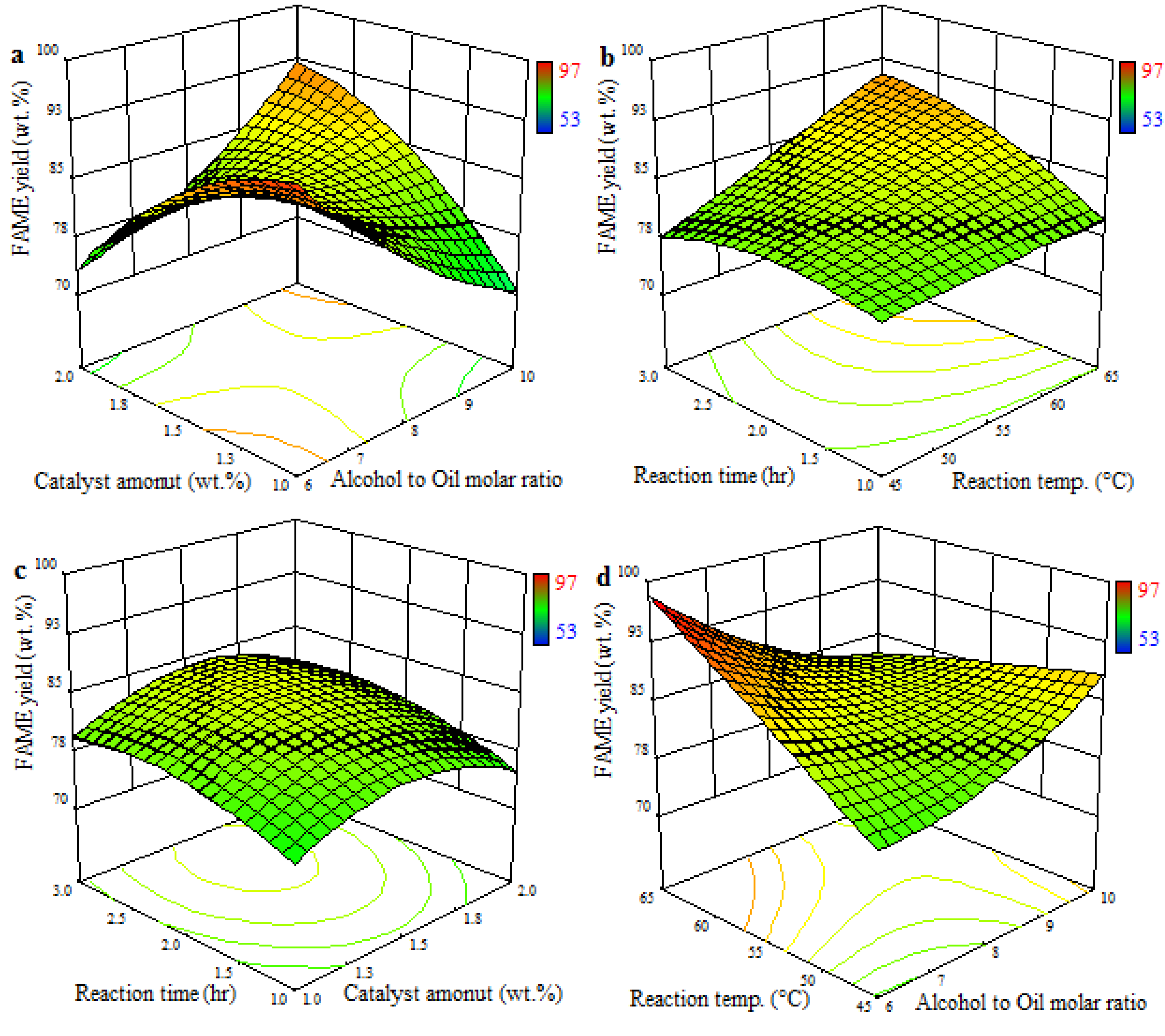


Figure 2: Surface plot of biodiesel conversion, (a) FAME yield verses catalyst amount and alcohol to oil molar ratio, (b) FAME yield verses reaction time and reaction temperature, (c) FAME yield verses reaction time and catalyst amount and (d) FAME yield verses reaction temperature and alcohol to oil molar ratio

3.2 ANOVA (analysis of variance) study for the transesterification process

The significance of transesterification output response was statistically studied using the ANOVA test and presented in Supplementary 4. The model was assumed to be significant if the p value was less than 0.05 at 95% confidence level [46]. Data fitting goodness was expressed in terms of the determination coefficient (R^2) and goodness of prediction (adjusted-R^2) [42]. The influence of oil molar ratio to alcohol, reaction temperature, time and catalyst ratio on FAME conversion were measured using the F-value [13]. The higher the F values of the variables, the higher their influence, as shown in Supplementary 4. In this study, B (catalyst) and D (reaction time) were found to be the most influencing variables compared to A (alcohol to oil ratio) and C (reaction temperature) as shown in Figure 3(a) as elucidated by Rashid et al. [47]. Thus, the steepest factor is the most influencing compared to others [48]. However, Junaid et al. [13] reported that the catalyst amount and alcohol to oil ratio were the most influencing factors compared to the reaction time and temperature. The predicted trends agreed well with the experimental results suggesting that the model can predicted the performance responses accurately as shown in Figure 3(b). The points are close towards the centre linear line. From the regression analysis, a response equation was produced in terms of the actual and the coded terms. The second order coded polynomial equation in terms of the most influencing variables on yield is given by Equation (7).

$$\text{FAME yield} = +88.86 - 6.18B + 5.05D - 4.61B^2 - 4.93D^2 + 9.66AB - 5.59AC \quad (7)$$

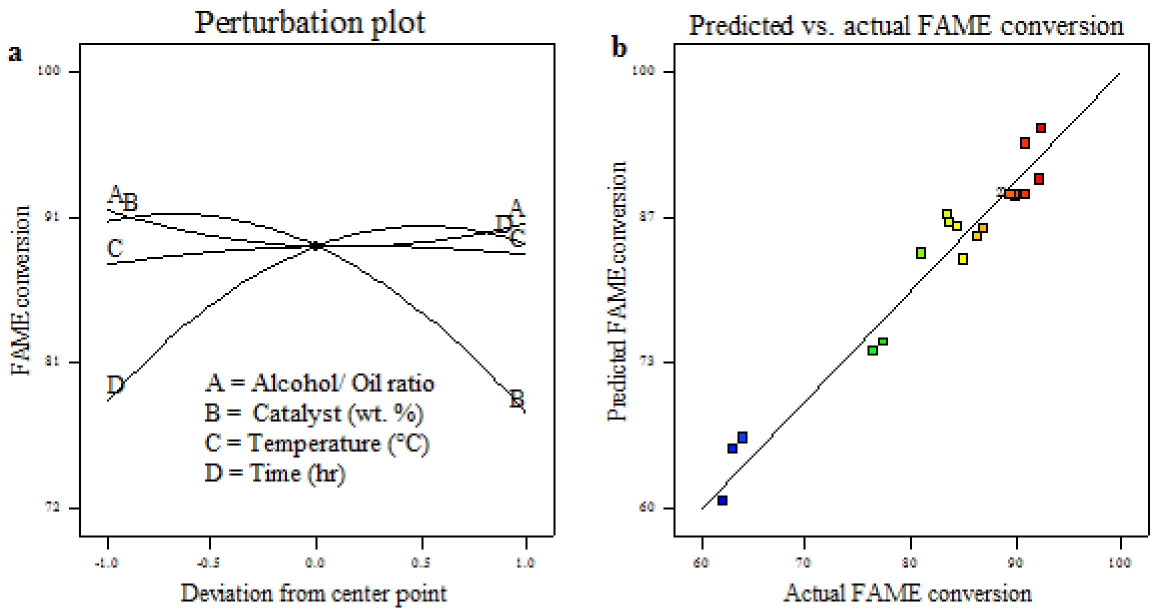


Figure 3: Perturbation plot (a) and transesterification predicted vs. actual FAME conversion (b).

3.3 Engine performance model analysis

The models studied were based on the ANOVA that provides numerical information for the p values. The regression model coefficients with p-value of 0.05 or higher is considered as an insignificant term for the model [22]. The p-values for different responses such as BT, BP, BTE, CO, CO_2, NO_x, EGT and O_2 are presented in Table 6. The insignificance of input factors over the output responses as the p value is greater than 0.05 is shown by the bold Time New Roman 10 point font. Using the regression coefficients, a second order polynomial models are developed in terms of the coded factors. The full second order polynomial function equations that contained all input variables are presented in Equations (8)- (16).

Table 6: ANOVA analysis of various responses indicating the p values

Source	Torque	Power	BSFC	BTE	CO	CO_2	NOx	EGT	O_2
Model	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
A	**0.2472**	0.0259	0.0128	**0.0754**	0.0183	0.0294	**0.9885**	**0.2545**	**0.7733**
B	**0.3022**	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	**0.5185**
C	<0.0001	<0.0001	<0.0001	0.0022	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
AB	**0.9265**	**0.2192**	**0.0541**	**0.0937**	**0.7206**	0.0004	**0.3261**	**0.3652**	0.0369
AC	**0.4098**	**0.2192**	**0.6666**	**0.7728**	0.0087	**0.4200**	**0.4828**	<0.0001	**0.0845**
BC	**0.9265**	<0.0001	<0.0001	**0.2477**	<0.0001	**0.4200**	0.0111	<0.0001	**0.8785**
A^2	0.0068	**0.0589**	0.0106	**0.2859**	<0.0001	<0.0001		<0.0001	**0.0583**
B^2	0.0045	0.0014	<0.0001	<0.0001	<0.0001	<0.0001		**0.2042**	0.0191
C^2	0.0004	0.0002	<0.0001	<0.0001	0.0001	<0.0001		0.0001	0.0007

$$\begin{aligned} BT = {} & 70.10 - 1.12A + 1.00B + 25.13C + 0.12AB - 1.13AC - 0.12BC \\ & + 3.89A^2 - 4.11B^2 - 5.36C^2 \end{aligned} \quad (8)$$

$$BP = 18.60 - 0.50A + 10.44B + 6.56C - 0.38AB - 0.38AC + 3.50BC + 0.58A^2 - 1.05B^2 - 1.30C^2 \quad (9)$$

$$BSFC = 271.80 + 19.63A - 80.19B - 57.44C - 22.25AB + 5.50AC + 52.88BC - 28.59A^2 + 123.54B^2 + 54.29C^2 \quad (10)$$

$$BTE = 30.17 - 0.75A + 3.76B + 1.39C + 1.00AB - 0.17AC - 0.68BC + 0.61A^2 - 6.67B^2 - 3.72C^2 \quad (11)$$

$$CO = 302.00 - 78.13A - 331.50B + 629\,C + 15.75AB - 124.75AC - 254.50BC + 323.62A^2 + 224.88B^2 + 197.63C^2 \quad (12)$$

$$CO_2 = 10.00 - 0.25A + 1.00B + 2.63C - 0.63AB - 0.12AC + 0.12BC + 0.81A^2 + 1.31B^2 - 0.94C^2 \quad (13)$$

$$NO_x = 440.00 + 0.13A + 120.75B - 74.63C - 12.13AB + 8.62AC + 33.13BC \quad (14)$$

$$EGT = 298.20 + 2.13A + 104.06B + 46.06C + 2.37AB + 27.13AC + 28BC + 24.65A^2 + 3.27B^2 - 11.47C^2 \quad (15)$$

$$O_2 = 7.98 + 0.050A - 0.11B - 3.38C - 0.54AB - 0.44AC + 0.037BC - 0.47A^2 - 0.60B^2 + 0.93C^2 \quad (16)$$

3.4 Model evaluation

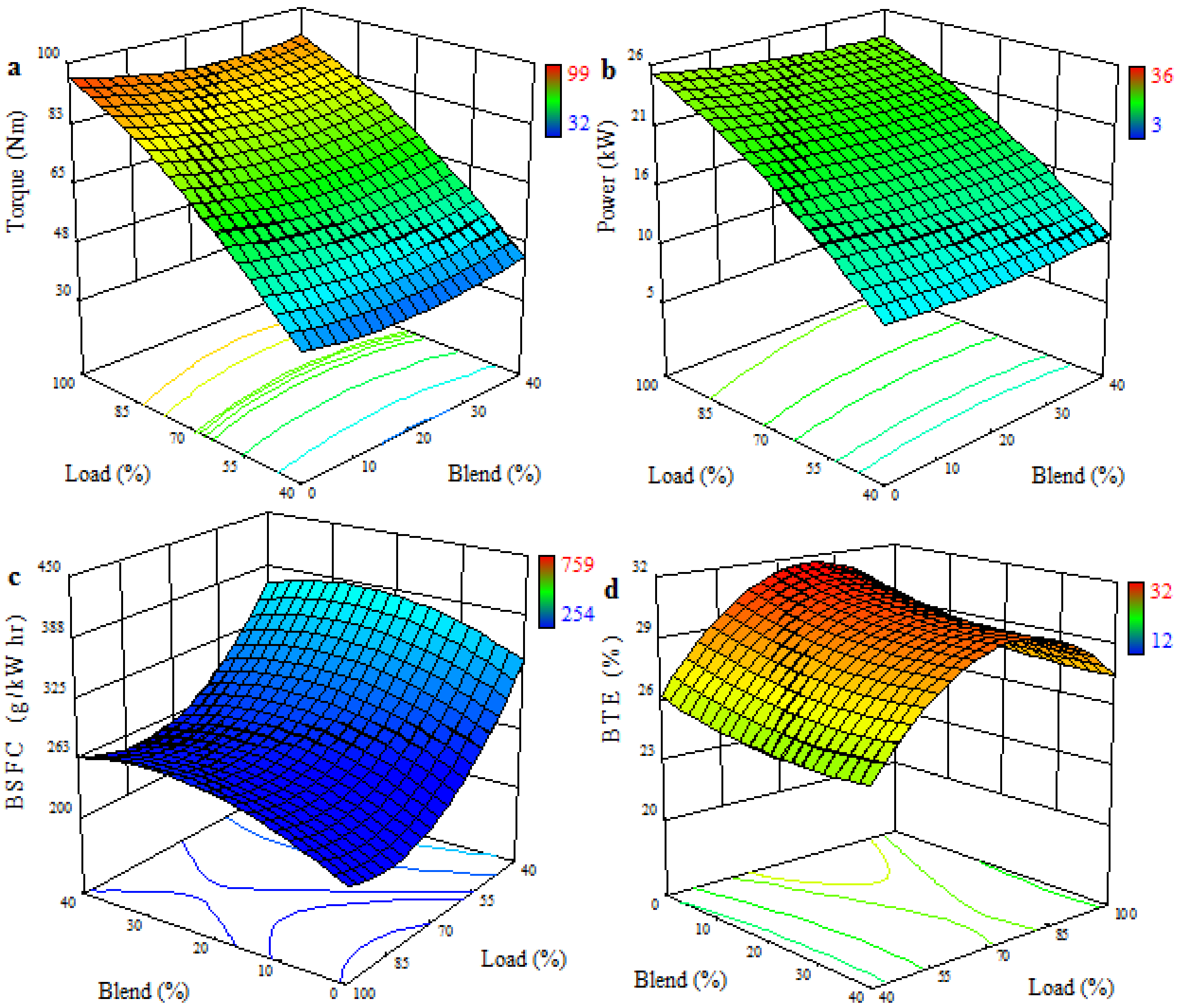
In order to validate the developed models, fitting test, data regression, significance analysis and individual model coefficients were studied and presented in Table 7. The quality of the fitted polynomial function models was expressed by the determination of coefficient R^2 that represents the proportion of variability of the response as a result of the input variables. However, as the model variables number increases, the determination coefficient (R^2) increases. Hence, it is recommended to use the adjusted- R^2, that decreases if unnecessary terms are added to the model [42]. In this study, R^2 and adjusted- R^2 were found to be close to each other, indicating low chances for a none significant terms to be included in the model [22]. On the other hand, lower values of CV (coefficient of variation) were observed suggesting a better precision and reliability of the experiments studied. In general, the model is assumed to be reasonably reproducible if its CV value is not greater than 10% [48]. The adequate precision value is a measure of the signal to the noise ratio of the response. A ratio greater than four indicates adequate model discrimination [49]. In this study, the response adequate precision was higher than four in all cases.

Table 7: Response surface model evaluation

Model	**BT**	**BP**	**BSFC**	**BTE**	**CO**	**CO_2**	**NOx**	**EGT**	**O_2**
Mean	67.47	17.76	342.03	25.57	653.12	10.56	440	305.94	7.91
Std. Dev.	3.79	0.84	44.74	1.62	123.04	0.43	34.26	7.27	0.69
CV	5.62	4.73	13.08	6.34	18.84	4.08	7.79	2.38	8.67
Model dgr.	Quadratic						2FI	Quadratic	
R^2	0.969	0.994	0.884	0.929	0.968	0.974	0.916	0.995	0.948
Adj. R^2	0.958	0.991	0.839	0.902	0.956	0.963	0.897	0.993	0.928
Pred. R^2	0.929	0.986	0.679	0.829	0.911	0.941	0.827	0.985	0.855
Adeq Prec	29.19	71.93	17.15	17.64	27.46	30.80	23.57	72.75	19.88

3.5 Effects of fuel blend ratio and load

The effects of blend combustion and engine load on the performance and emissions are depicted in Figure 4(a-h). By increasing the blend ratio of biodiesel to diesel up to 40%, the BT, BP, BTE and CO were reduced by 1.6%, 1.4%, 1.5% and 6.7% respectively. Whereas the BSFC, CO_2, NOx, EGT and O_2 increased by 1.7%, 1.1%, 1.2%, 1.3% and 1.2 % respectively as compared to the diesel fuel. This is due to the higher density, viscosity and surface tension, and lower heating values of the blend increasing the injected fuel amount [50]. This is turn increases the BSFC and decreases the BT, BP and BTE as a result of atomization and combustion deterioration [25, 51]. The reduction of CO is attributed to the decrease of air-fuel equivalence ratio due to an increase in BSFC. An increase in CO_2, EGT, NOx and O_2 can be explained from the oxygen content, poor volatile constituent of the fuel and the change of air-fuel equivalence ratio. The oxygen content in the biodiesel fuel contributed to the hydrocarbon oxidation and resulted in complete combustion, leading to higher CO_2 emission. On the other hand, an increase in EGT and NOx is attributed to the poor volatile constitutes in the biodiesel fuel, which led to a continuous burning until the late combustion phase [27, 51]. Similarly, the change in the air- fuel equivalence ratio as a consequence of higher BSFC advanced the premixed combustion phase and increased the combustion pressure and temperature, resulting in an increase in NOx and EGT. O_2 emission also increased as the biodiesel percentage increased due to the presence of the chemically bound oxygen in the biodiesel. Hence, more O_2 emission is expected in the exhaust compared to the diesel fuel [52]. The responses of ANOVA in Table 6 indicates the significance of the blend and load individually. However, their interactive effects are found to be insignificant except for CO and EGT as the values of p is less than 0.05 [23].



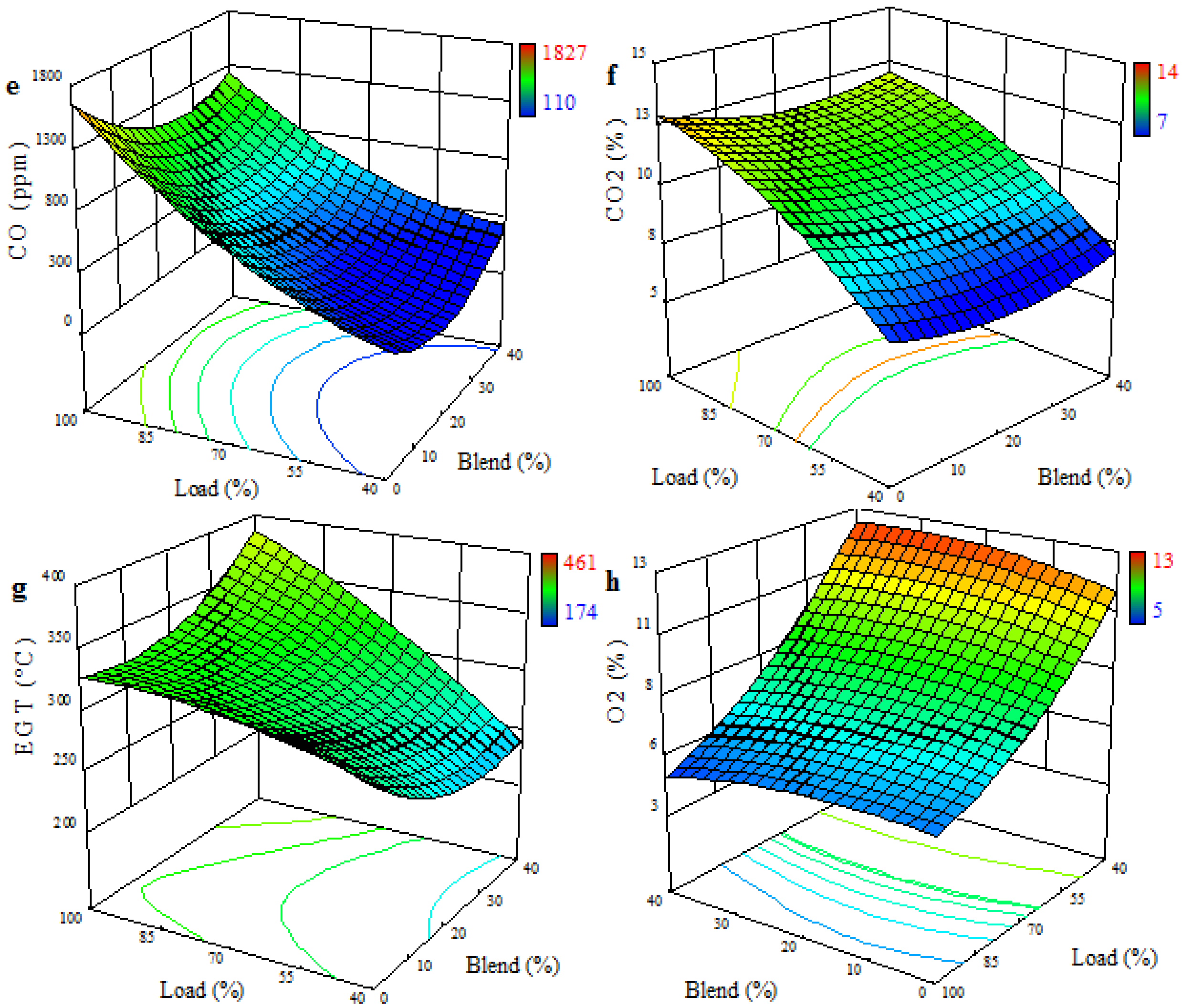
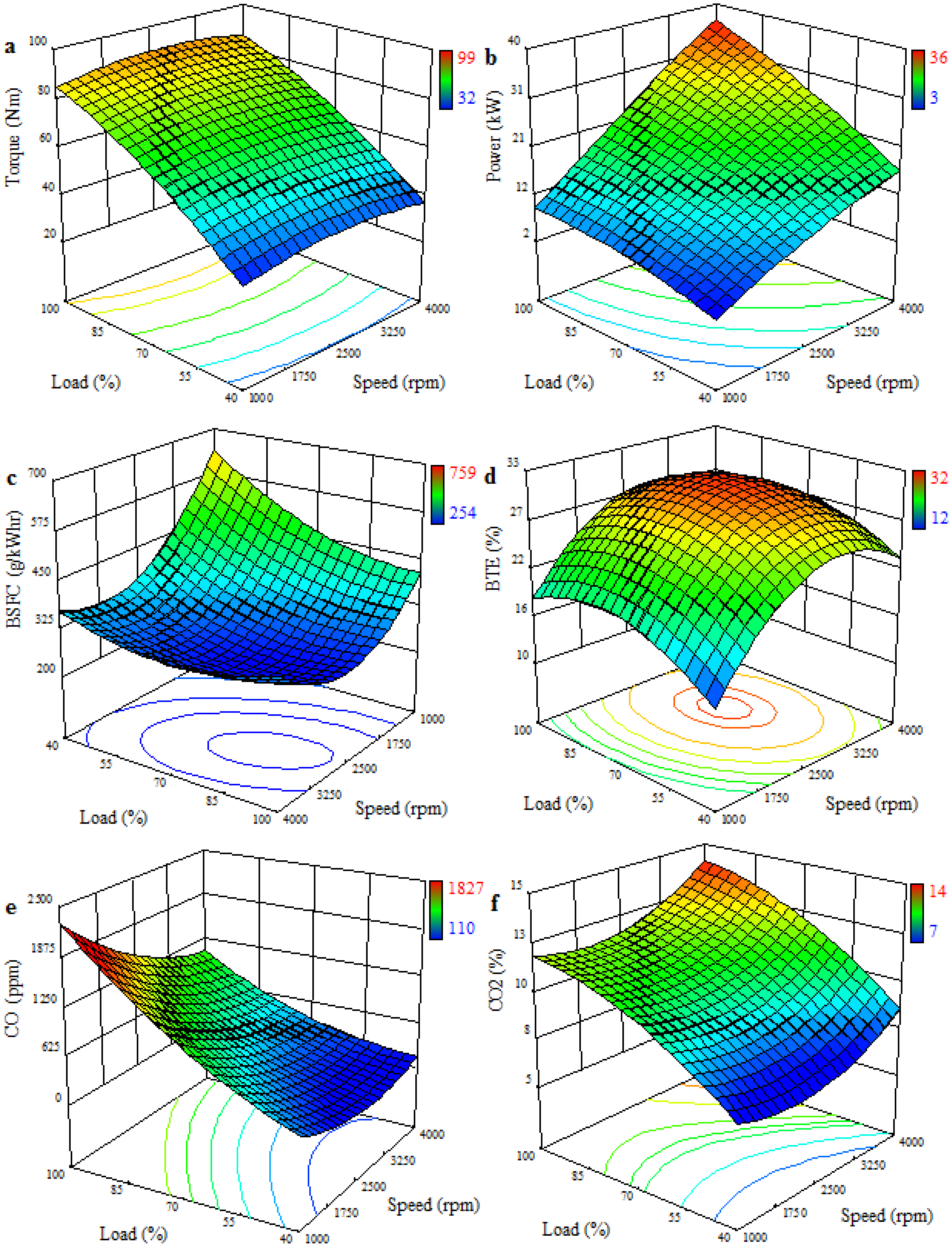


Figure 4: Interactive effect of blend and load (a) BT verses fuel blend and engine load, (b) BP verses engine load and fuel blend, (c) BSFC verses fuel blend and engine load, (d) BTE verses fuel blend and engine load, (e) CO verses engine load and fuel blend, (f) CO_2 verses engine load and fuel blend, (g) EGT verses engine load and fuel blend and (f) O_2 verses fuel blend and engine load.

3.6 Effects of engine load and speed

The combined effects of engine speed and engine load on BT, BP, BSFC, BTE, CO, CO_2, NOx, EGT and O_2 are shown in Figure 5 (a-h). As the engine speed increased from 1000 rpm to 2500 rpm, there was a reduction in the BSFC and CO with an increase in the BT, BP, BTE, CO_2, NOx, EGT and O_2 which is in agreement with [52]. However, beyond 2500 rpm, an opposite trend was noticed for the responses. More so, lower BSFC and CO, and higher BT and BTE were observed at 2500 rpm. As the engine load increased, the BT, BP, BTE, CO, CO_2 and EGT increased while the BSFC and O_2 decreased. Although the engine load and speed were found to have strong effects on the emissions and performance characteristics individually, their combined effects were found to be insignificant except for the BP, BSFC, CO, NOx and EGT as shown in Table 6 with the p values greater than 0.05 (95% confident level). This was in agreement with the findings of Bhattacharya et al. [21]. Ganapathy et al. [53] investigated the effects of engine speed and load using Jatropha biodiesel and found strong effect of engine speed and load on the BSFC, BTE, CO, THC and NO individually, however their interaction effects were found to be insignificant except on BSFC.


a
Torque (Nm)
Load (%)
Speed (rpm)
99
32
b
Power (kW)
Load (%)
Speed (rpm)
36
3
c
BSFC (g/kWhr)
Load (%)
Speed (rpm)
759
254
d
BTE (%)
Load (%)
Speed (rpm)
32
12
e
CO (ppm)
Load (%)
Speed (rpm)
1827
110
f
CO2 (%)
Load (%)
Speed (rpm)
14
7

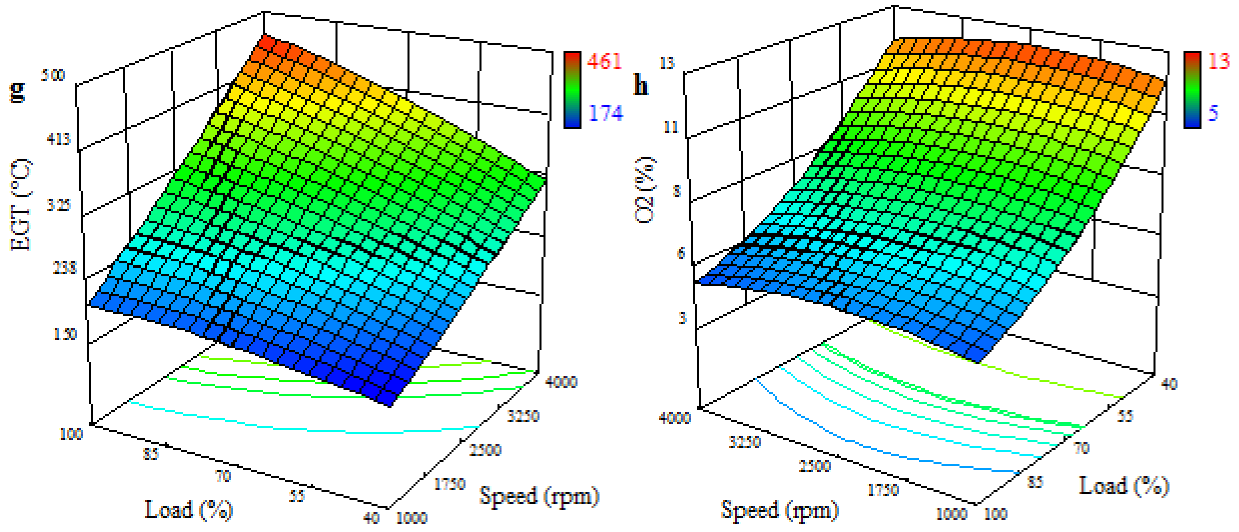
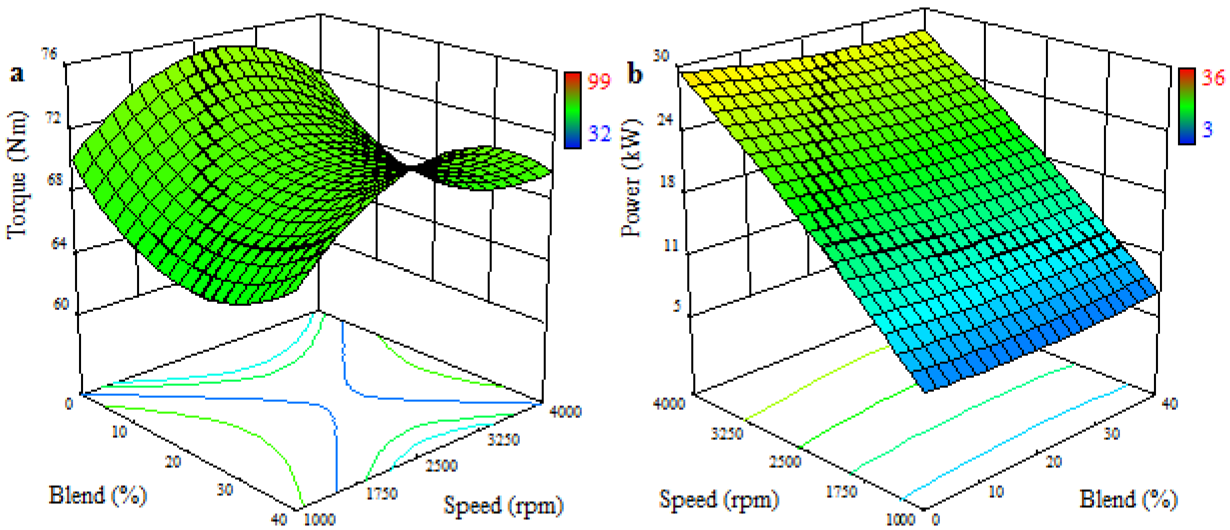


Figure 5: Interactive effect of load and speed, (a) BT verses engine load and speed, (b) BP verses engine load and speed, (c) BSFC verses engine speed and load, (e) CO verses engine load and speed, (f) CO_2 verses engine speed and load, (g) EGT verses engine load and speed and (h) O_2 verses engine speed and load.

3.7 Effects of engine speed and blend ratio

The effects of the fuel blend ratio and the engine speed on the performance and emissions parameters such as BT, BP, BSFC, BTE, CO, CO_2, EGT and NOx are shown in Figure 6 (a-h). It can be seen that increasing the engine speed from 1000- 4000 rpm and the fuel blend ratio from 0- 40% reduced the BT, BP, BTE, and increased the BSFC, CO and EGT. The reduction in the BT, BP and BTE is attributed to the biodiesel heating value which is 9.6% lower compared to the diesel fuel, higher density and higher viscosity [50]. With reference to the effects of fuel blend ratio and engine speed, the discussion in Sections 3.5 and 3.6 could be used for the stated results. The ANOVA for the responses in Table 6, indicates that both engine speed and fuel blend ratio have significant effects on the responses, however, their combined effects are insignificant over all responses except on the CO_2 and O_2. This is in agreement with results reported by [54, 55], who claimed insignificant combination effects of CO, O_2, CO_2 and NOx when a methyl tallow blended diesel fuel was used. Ali et al. [56] also claimed that the fuel blend ratio and engine speed had significant effects on the BT, BP, BSFC, CO, THC and NOx except CO_2 individually, while there was no interaction effect between the fuel blend ratio and engine speed over the responses being observed.



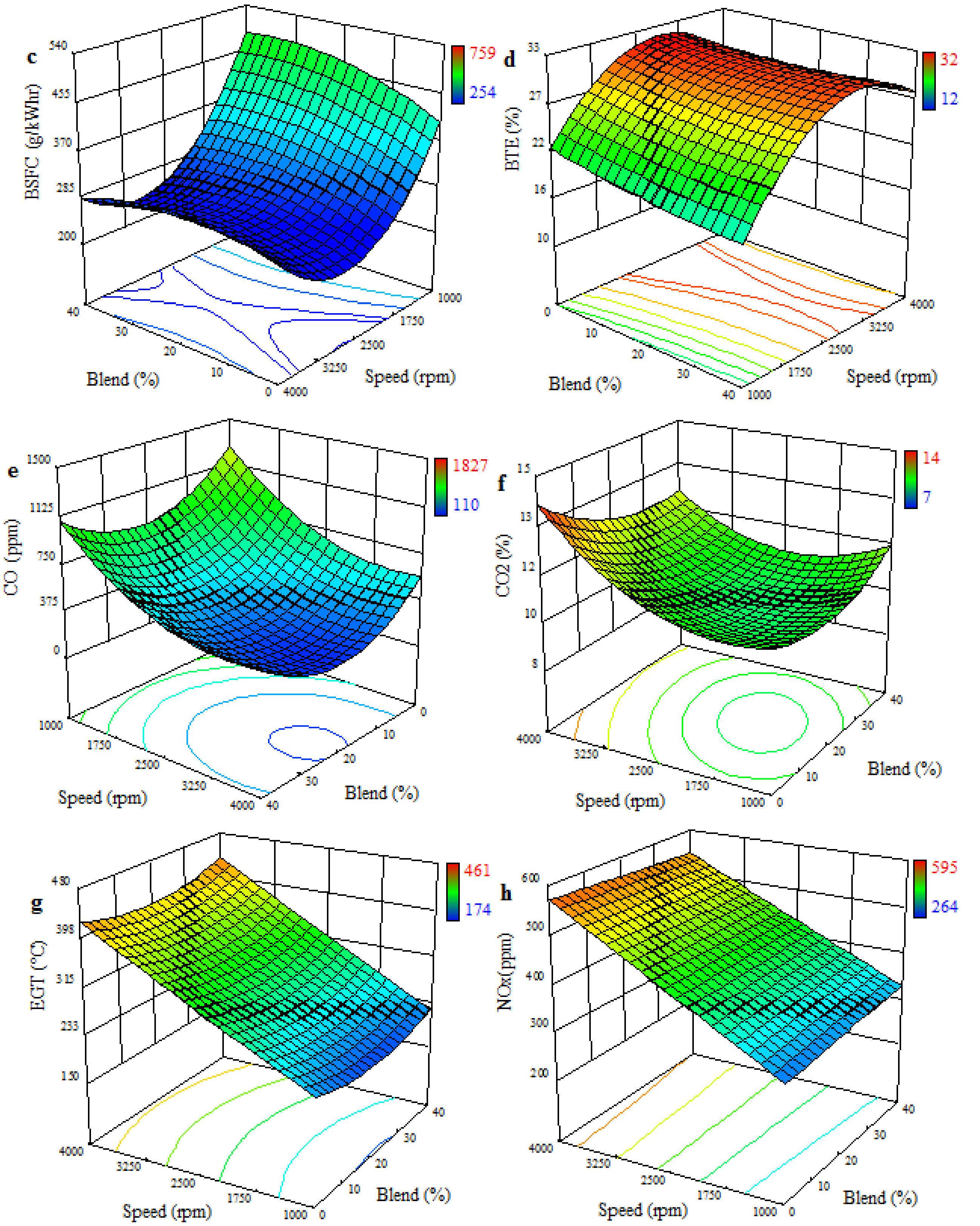


Figure 6: Interactive effect of engine speed and fuel blend ratio (a) BT verses fuel blend and engine speed, (b) BP verses fuel blend ratio and engine speed, (c) BSFC verses engine speed and fuel blend ratio, (d) BTE verses engine speed and fuel blend ratio, (e) CO verses fuel blend ratio and engine speed, (f) CO_2 verses fuel blend ratio and engine speed, (g) EGT verses fuel blend ratio and engine speed and (h) NO_x verses engine speed and fuel blend ratio.

3.8 Validation of optimization results

The used optimization criteria such as the lower and upper limits, weight, response goal set and importance of each factor are presented in Supplementary 5. In the optimization based desirability approach, the solution with high desirability is preferred [22, 23]. A maximum desirability of 0.96 is obtained at a fuel blend ratio of 18%, engine speed of 2320 rpm and engine load of 82% which can be considered as the optimum parameters for the tested IDI engine which has rated speed of 2500 rpm, maximum BT of 110 Nm and maximum BP of 44 kW at 4800 rpm. In order to validate the optimized results, another set of experiments was conducted. The actual data of each response was averaged and presented in Table 8. The validation results are considered to be accurate as the predicted values are in a good agreement with the actual values. Moreover, the obtained results are compared with previous optimized studies [23, 53, 57] and found to be in a good agreement.

Table 8: Optimum performance and emissions validation and comparison with previous studies.

Parameters	**This study**			**Sivaramakrishnan and Ravikumar [23]**		**Jagannath et al. [57]**		**Ganapathy et al. [53]**	
	Values			Values		Values		Values	
	Predicted	Actual	% error	Predicted	Actual	Predicted	Actual	Predicted	Actual
Blend (%)	18	18	-	10	10	20	20	-	
Speed(rpm)	2320	2320	-	-	-	-	-	1801	
Load (%)	82	82	-	3.81	3.81	3.5	3.5	11.43	
CR	-	-	-	17.9	17.9	16	16	-	
BT (Nm)	81	80	-1.2	-	-	-	-	-	
BP(kW)	20	20	-			-	-	-	0.1-2% mean errors
BSFC(g/kWhr)	263	264	0.37	271.8	278.3	301	303	287.5	
BTE (%)	30	30	-	33.65	33.24	27.1	26.8	30.96	
CO (ppm)	665	675	1.48			-	-	76	
CO_2 (%)	11	11	-	-	-	-	-	-	
THC (ppm)	-	-	-	158.03	156.86	-	-	5.27	
NOx (ppm)	393	391	-0.51	938.3	940.45			321.69	
EGT (°C)	300	297	-1.01	-	-	250	252	-	
O_2 (%)	7	7.1	1.3	-	-	-	-	-	

4. CONCLUSION

In this study, the rubber seed/palm oil biodiesel synthesis was analysed. The methyl ester produced form the blend of the two oils was characterized and found to be in a good agreement with the ASTM and EN standards. In addition, the effect of the obtained methyl ester blended diesel on the emissions and performance of IDI engine was investigated. Increasing the engine speed and the engine load was found to increase the BT, BP, BTE, CO_2, NOx and EGT and to decrease the BSFC and O_2. However, increasing the fuel blend ratio had an opposite trend to the engine load and engine speed. On average, biodiesel blends produced lower BT (0.97- 1.6%), BP (0.94- 1.4%), BTE (0.76- 1.5%) and CO (0.93- 6.7%), but higher BSFC (0.93- 1.7%), CO_2 (0.95- 1.1%), NOx (0.97- 1.2%), EGT (1.1-1.3%) and O_2 (0.3- 1.2 %) at full load compared to the diesel fuel. At part engine load, performance and emissions were found to be slightly different but the differences were relatively small and could be considered. Compared to the engine speed and fuel blend, engine load was found to be the most influential variable individually and in combination with other variables. A higher desirability of 0.96 was obtained at an engine load of 82%, engine speed of 2320 rpm and fuel blend ratio of 18%, where the values of BT, BP, BSFC, BTE, CO, CO_2, NOx, EGT and O_2 are found to be 81 Nm, 20 kW, 263 g/kWh, 30%, 665 ppm, 11%, 393 ppm, 300°C and 7% respectively. In conclusion rubber seed/ palm oil mixture can be considered as a potential source for biodiesel production and a fuel blend ratio of 18% is optimum for the tested IDI engine with this biodiesel.

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ABBREVIATIONS

RSM: Response surface methodology
IDI: Indirect injection diesel engine
BBD: Box- Behnken design
RSM: Response surface methodology
BT: Brake torque
BP: Brake power

BSFC: Brake specific fuel consumption
BTE: Brake thermal efficiency
CO: Carbon monoxide
CO_2: Carbon dioxide
NO_x: Oxides of nitrogen
EGT: Exhaust gas temperature
O_2: Oxygen
THC: Total hydrocarbon
IT: Injection timing
IP: Injection pressure
DoE: Design of experiments
ANN: Artifical neural network
BTDC: Before top dead center
ID: Direct injection diesel engine
JB: Jatropha methyl ester
MB: Moringa oleifera methyl ester
PB: Palm oil biodiesel
PBJB: Palm- jatropha combined biodiesel
CIB: Calophyllum inophyllum biodiesel
RB: Rapeseed methyl ester
HB: Hazelnut methyl ester
SB: Soybean biodiesel
CB: Coconut biodiesel
WSB: Waste sunflower oil biodiesel
CAB: Canola biodiesel
PPB: Pongamia pinnata methyl ester
MOB: Mustard oil biodiesel
KB: Karajan biodiesel
POB: Polanga oil biodiesel
WCB: Waste cooking oil biodiesel
SOB: Sunflower oil biodiesel
CSB: Cotton seed oil biodiesel
AOCS: American Oil Chemistry Society
HC: hydrodynamic cavitation reactor
B10%: 90% diesel +10% biodiesel
B20%: 80% diesel +20% biodiesel
B40%: 60% diesel + 40% biodiesel
ASTM: American society for testing and material
EN: European standard
ECU: Engine control unit
CCD: Central composite design
ANOVA: Analysis of variance
R^2: Determination coefficient
R^2_{adj}: Adjusted coefficient
CV: Coefficient of variation

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Appendix

S 1: Description of oils blend based biodiesel, engine performances and emissions

Fuel used and test condition	Engine type	Results compared to base diesel fuel		Remarks
		Performance and emissions	**Refs.**	
JB (Jatropha biodiesel), MB (moringaoleifera oil biodiesel), speeds (1000- 4000 rpm) and blends (JB10, MB10 and full load).	Mitsubishi Pajero model 4D56T, IDI, 4 cylinder, 4- stroke, water cooled, maximum power of 55kW and CR 21:1	JB and MB shows 4- 5% lower BP, 3- 5% higher BSFC, 11-14% lower CO, 12- 16% lower THC, 7- 9% higher NOx and 5- 7% higher CO2 compared to diesel fuel.	[25]	JB and MB are potential biodiesel production sources. The properties were in line with ASTM and EN standards.
PB (Palm oil biodiesel), JB, varied speeds (1400- 2200 rpm) and different blends (PB10, PB20, JB10, JB20, PBJB5 and PBJB10).	Single cylinder, 4-stroke, water cooled, DI, Yanmar TF 120-M, rated power of 7.7 kW at 2400 rpm and CR 17.7:1	Combined PBJB5 and PBJB10 shows 9.53% and 20.49% lower CO, 3.69% and 7.81% lower THC, 7.55% and 19.82 % higher BSFC, 1.07% and 1.12% lower BP, respectively than diesel fuel.	[26]	Combined biodiesel showed better emissions compared to diesel fuel and can be used without engine modification.
PB, CIB (calophylluminophyllum biodiesel), varied loads (10, 12, and 15%), varied speeds (1000- 1500 rpm), blends (PB5, PB10, PB20, CIB5, CIB10 and CIB20).	Mitsubishi Pajero, DI, water cooled, 4 cylinder, maximum torque of 132 Nm at 2000 rpm, maximum power of 50 kW at 4000 rpm and CR ratio 21:1	PB and CIB have shown higher BSFC and NOx whereas BTE, CO, EGT and THC are lower compared to diesel fuel.	[27]	Negligible BSFC difference at idling speed of 1500 rpm. CIB has registered BTE better than PB.
RB (rapeseed biodiesel) and HB (biodiesel hazelnut oils biodiesel) different speeds (1200- 2200 rpm), different blends B1 (RB 50%), B2 (HB 50%), B3 (RB 25% + HB 25%) and full load.	4 cylinder, 4 stroke, DI, maximum power: 46 kW at 2400 rpm, maximum torque of 216 Nm at 1400 rpm and CR of 16.1:1	Blends of B1, B2, and B3 have shown 0.78- 1.19% lower torque, 3.07- 6.97% higher BSFC, 9.04-15.53% lower CO, 0.39- 2.9% higher CO2, 2.96- 7.82% higher NOx and 37.18- 46.29% lower smoke compared to diesel fuel.	[28]	B1 torque and BSFC are shown to be similar to those of diesel fuel. RB and HB methyl ester can be used together in existing diesel engine.
RB and SB (soybean oil biodiesel), different speeds (1100- 2400 rpm) and different IPs (250, 300, 350 bar) and full load).	4 cylinder, 4-stroke, DI, maximum torque of 216 Nm at 1400 rpm, maximum power of 46 kW at 2400 rpm and CR of 16.1:1	RB and SB have lesser CO, smoke and higher NOx at all IPs compared to diesel fuel. BP is shown to be 6- 12% and 5- 10% lower and BSFC is shown to be 6- 14% and 3- 10% higher for RB and SB respectively than diesel fuel.	[29]	From emissions point of view SB has lesser exhaust emissions compared to RB and diesel fuel.
CB (coconut biodiesel), PB, varied speeds (1400- 2400 rpm), different blends (PB30, CB30 and PB15CB15) and full load.	Single cylinder, 4- stroke, water cooled, DI, Yanmar TF 120M, rated power of 7.7 kW at 2400 rpm and CR of 7.7:1	Biodiesel blends have shown 3.92- 4.71% lower BP, 3.84- 5.03% lower BTE, 8.55-9.03% higher BSFC, 3.13- 5.6% higher NOx, 13.75- 17.97% lower CO and HC respectively compared to diesel fuel. PB15CB15 achieved the lowest BSFC over PB and CB individually.	[30]	Combined palm coconut blend have superior emissions and performance over PB and CB biodiesel individually.
PB and CB optimized condition (PB: 87.6 and CB: 12.4), blend of 20%, different speeds (1000- 4500 rpm and full load).	4 cylinder, IDI turbocharged diesel engine, water cooled, maximum BT of 185 Nm at 2000, rated BP of 65 kW at 4200 rpm and CR of 21:1	20% blend has shown 0.3- 1% higher BP, 2% higher BSFC, 0.5- 6% higher BTE, 10- 60% lower CO, 4- 7.5% lower CO2, 20- 80% lower THC, 3.4- 4.8% higher NO and 5.6- 10.9% lower smoke compared to fossil diesel fuel.	[31]	Better overall properties compared to PB and CB individually.

HB, WSB (waste sunflower oils biodiesel) varied blends (B5, B15 and B25), varied speeds (1500- 3000 rpm) and different loads (100%, 75% and 50%).	4 cylinder, 4-stroke, water cooled, IDI, Ford XLD 418T,maximum BT of 152 Nm at 2200 rpm, maximum BP of 55 kW at 4500 rpm and CR of 21.5:1	The blended fuel's BT, PB and BSFC are found to be higher at full and partial loads. BTE is reported to be lower at 100% load while higher at partial loads. EGT, CO2, NOx and CO are found to be higher at full load, whereas the difference is negligible at partial loads compared to diesel fuel.	[32]	17.5% blend addition to diesel fuel is the optimum for higher BP and BTE.
CAB (canola biodiesel), HB, constant speed of 2200 rpm (maximum BT speed), different blends (B5 and B10) and different loads (25, 50, 75 and 100%).	1 cylinder, 4- stroke, DI, Antor (6 LD400 model), air cooling, maximum BT of 19.6 Nm at 2200 rpm, maximum BP of 5.4 kW at 3000 rpm and CR of 18:1	BTE and BSFC are found to be similar with B5 while lesser with B10 compared to diesel fuel. No significant changes of CO, THC and smoke with B5 at partial loads. No significant effect was noticed for B5 and B10 over CO2 emission.	[33]	5- 10 vol. % of CAB and HB can be used without engine modification.
SB, CAB and PB, varied blends, B1 (SB33.3, CAB33.3, PB33.3), B2 (SB10, CAB10, PB10), B3 (SB20, CAB20, PB20), B4 (SB25, CAB25, PB25) and different speeds (1000- 2400 rpm).	3 cylinder, 4- stroke , Fiat diesel engine, maximum BT of 195 Nm at 1400 rpm, maximum PB of 36 kW at 2000 rpm and CR of 17:1	The tested biodiesel fuels have shown, 3.3% lower BP, 8.2% higher BSFC, higher NOx and CO2 and lower CO as compared to diesel fuel.	[34]	Up to 25% diesel usage can be substituted by blending SB, CAB and PB.
PPB (pongamiapinnata biodiesel), MOB (mustard oils biodiesel), varied blends A (PPB5, MOB5), B (PPB10, MOB10), C (PPB20, MOB20), D (PPB30 MOB30), E (PPB40, MOB 40) and F (PPB50, MOB 50), speed of 3000 rpm and various loads (0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4 and 2.8 kW).	Single cylinder, Kirloskar engine, maximum speed of 3000 rpm, maximum BP of 4.5 hp, air cooling and CR of 18:1	BTE and mechanical efficiency of blend A are noticed to be higher, whereas for blends B and C are similar to those of diesel fuel. CO2 and CO are found to be lower while smoke, THC and NOx are higher.	[35]	Blends A, B and C can be used as an alternative fuel for diesel engine.
JB, KB (karajan biodiesel), POB (polanga oil biodiesel), different blends,JB20, JB50, JB100, KB20, KB50, KB100, POB 20, POB50, POB100 and different load (0, 50 and 100%)	Single cylinder, Kirloskar engine model DAF 8, 4 – stroke, air cooling, rated BP of 6 kW, rated speed of 1500 rpm and CR of 17.5:1	Blend of KB, JB and POB have shown lower ignition delay of 4.5- 6.3°, 4.2- 5.9° and 4.2- 5.7° respectively compared to diesel fuel.	[36]	POB has higher peak pressure and shorter ignition delay. However there was no performance and emissions work conducted.
CAB, HB, WCB (waste cooking oil biodiesel), different speeds (1750- 4500 rpm) and full load condition.	4 cylinder, Land Rover turbocharger DI 110, water cooling, maximum BT of 235 Nm at 2100, maximum power 82 kW at 3850 rpm and CR of 19:1	Biodiesel fuels have shown 25.5 % lower CO, 3.73 % lower NOx, 23.66- 52.31 % lower smoke density and 9.31 % lower EGT compared to diesel fuel.	[37]	CAB, HB and WCB can be used in exiting TDI without modification. However, there was no performance and combustion work conducted.
SOB (Sunflower oil biodiesel), CSB (cotton seed oil biodiesel), different blends (SOB10, SOB20, COB10, COB20), different speed (800- 2600 rpm) and different loads (20 %, 40 % and 60%)	6 cylinder, Mercedes- benz, DI, 4-stroke, water cooled, maximum BT of 840 Nm at 1250- 1500 rpm, Maximum BP of 177 kW at 2600 rpm and CR of 18:1.	Biodiesel blends have shown, lower smoke density, higher NOx, lower CO and higher THC compared to diesel fuel.	[38]	CSB showed lower emissions compared to SOB and fossil diesel fuel.

S 2: Transesterification design plan, experimental and predicated FAME yield

Exp. run	Alcohol/ oil ratio	Catalyst amount (wt. %)	Reaction temp. (°C)	Reaction time (hr)	FAME yield (%)	
					Actual	Predicted
1	6	1.00	45	1.00	92	90.88
2	8	2.34	55	2.00	71	72.19
3	6	1.00	65	1.00	97	95.37
4	8	1.50	55	2.00	83	84.17
5	10	2.00	45	1.00	85	84.38
6	8	1.50	55	0.32	72	73.39
7	6	2.00	65	3.00	90	88.37
8	8	1.50	55	3.68	80	81.59
9	10	1.00	65	3.00	70	68.37
10	6	2.00	45	3.00	53	51.88
11	11.36	1.50	55	2.00	88	89.91
12	8	1.50	55	2.00	83	84.17
13	10	2.00	65	1.00	84	82.57
14	4.64	1.50	55	2.00	92	93.99
15	10	1.00	45	3.00	79	78.58
16	8	0.66	55	2.00	70	71.59
17	8	1.50	55	2.00	90	84.17
18	8	1.50	38	2.00	77	77.60
19	8	1.50	55	2.00	84	84.17
20	8	1.50	55	2.00	85	84.17
21	8	1.50	72	2.00	87	89.79