

Performance Optimisation of Air Cooled Diesel Engine with Simarouba Biodiesel Blends as Substitute Fuel Using Response Surface Method

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Abstract: In the present study the usability of simarouba biodiesel blends in air cooled diesel engine and performance optimization of engine is intended in terms of percentage blend and Brake Power (BP). An air cooled diesel engine of 4.4 kW rated power running at constant speed of 1,500 rpm is chosen for conducting the experiments. Experiments are conducted with diesel and biodiesel blends (10%, 20% and 30% by volume) at different load conditions. The performance parameters like Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC) and emissions-Carbon Monoxide (CO), Hydro Carbon (HC), Oxides of Nitrogen (NO_x), and Filter Smoke Number (FSN) are analyzed. The performance of engine is slightly improved in terms of marginal improvement in BTE and BSFC with 20% biodiesel blend as compared to diesel. Emissions are considerably reduced with all blends compared to diesel. The performance optimization of engine is performed using desirability approach of Response Surface Method (RSM). Statistical models correlating percentage biodiesel blend, BP and responses (BTE, BSFC, CO, HC, NO_x, and FSN) are developed.

Keywords: Biodiesel Blends, Diesel Engine, Performance and Emissions, RSM

1. Introduction

1.1. Biodiesel

Biodiesel is a mono-alkyl esters of long chain fatty acids obtained from vegetable oils or animal fats. It is renewable, biodegradable, environmental friendly, non-toxic and easily available fuel [1]. Biodiesel has low volatility because of higher molecular weight of the triglyceride [2] and has a slight range of viscosity changes with temperature. There are many ways to produce biodiesel from vegetable oil, such as pyrolysis, dilution, micro emulsion and transesterification. The transesterification process is the most feasible and economical process as reported in the literature [3, 4]. Biodiesels from Soya, Sunflower, Jatropha, Honge, Rubber seed and Simarouba are commonly considered as substitute for diesel fuel [1, 2].

Simarouba belongs to the family of Simaroubaceae Quasia, commonly known as paradise tree originated in North America. It is a medium sized tree generally attains a height of 20-25 m and trunk diameter of 50-90 cms approximately. It can grow under different climatic conditions like warm, humid and tropical regions. Simarouba seed contains approximately 55-65% oil content. The oil yield is 1500-2000 kg/ha/year for a plant spacing of 5m x 5m. Seeds of simarouba are used to produce potential biodiesel and ethanol. Bio gas is produced using simarouba fruit pulp, oil cake, leaf litter etc. Simarouba being rich in nitrogen, phosphorus, and potash can be used as valuable organic manure. It is also used in the manufacture of soaps, detergents and lubricants in industries. Simarouba is gaining economic importance in countries such as India, China, Myanmar and so on due to its properties comparable to diesel and other biodiesels [5-7]. Since simarouba is a newly found

oil, there exist a large scope for studies on performance and emission characteristics of this oil. Hence present investigation is carried out on usage of blends of simarouba biodiesel in unmodified diesel engine.

1.2. Characterization of Simarouba Biodiesel Blends

Transesterification is the chemical reaction of fat or oil with an alcohol to form esters[5]. Simarouba seeds are collected from commercial sources and the crude oil is extracted using mechanical expeller. Since free fatty acid content of simarouba oil is found to be 1.69% (<2%), single stage alkaline esterification process is adopted [5]. Sodium hydroxide (NaOH) is used as catalyst to enhance the chemical reaction. Molar ratio of 6:1 (oil to methanol) and 1% of catalyst out of oil weight are considered for the

process [5]. Transesterification is performed in a 2000 ml reaction flask equipped with glass reactor, magnetic stirrer, condenser and heater with temperature controller unit and a thermometer. NaOH catalyst is dissolved in methanol by stirring in a flask. 1000 ml of simarouba crude oil is heated in a reaction flask till it reached 65°C and mixture of methanol and NaOH is then added and stirred for about 2 hours. The mixture is allowed to settle down for 24 hours. After this process, glycerin is separated and biodiesel layer is rinsed with warm water. In order to remove excess water and alcohol, the biodiesel is further heated to about 100°C. Flow diagram and chemical reaction of transesterification are shown in Figure 1 (a) and (b) respectively. Table 1 presents the properties of simarouba biodiesel and biodiesel blends and are compared with diesel.

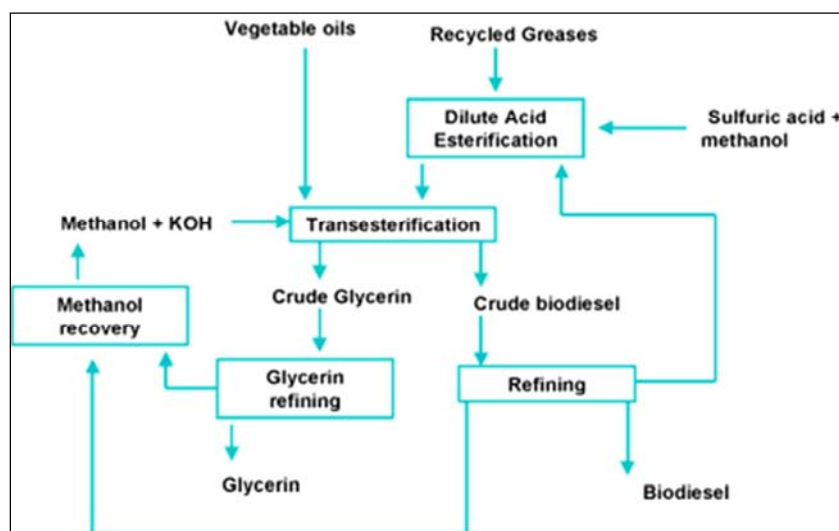


Figure 1a. Transesterification flow chart.

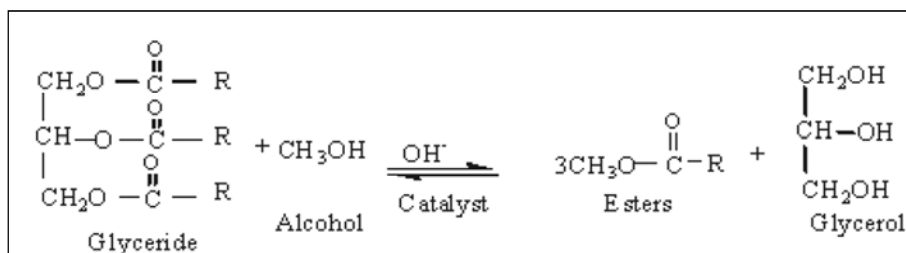


Figure 1b. Chemical reaction of transesterification.

Table 1. Properties of Simarouba biodiesel, biodiesel blends compared with diesel.

Testing method	ASTM D841	ASTM D240	ASTM D445	ASTM D941	ASTM D941
Blend	Density (kg/m ³)	Calorific Value (MJ/kg)	Viscosity (Cst) @ 40°C	Flash point (°C)	Fire point (°C)
D	840	42.500	2.54	54	64
SBD10	841	42.410	2.73	60	72
SBD20	843	42.270	3.1	65	79
SBD30	846	42.120	3.49	69	83
SBD100	842	38.443	4.87	162	168

2. Experimental Studies

Experiments are conducted on a 4-stroke single cylinder air

cooled, diesel engine (Kirloskar TAF1) coupled with electric dynamometer. Air flow rate is measured using air box fitted with a sharp edge orifice meter. Fuel flow rate is computed by noting the time for 20 cc of fuel consumption by the engine.

Engine emissions such as carbon monoxide (CO), carbon dioxide (CO₂), hydro carbon (HC) and NO_x are measured using AVL 444 DI gas analyzer. Smoke Opacity (SO) is measured using AVL 415 smoke meter. Test engine with gas analyzer and smoke meter is shown in Figure 2. Specifications of the test engine are presented in table 2. The experiments are conducted with diesel and SBD10 (10% simarouba biodiesel+90% diesel), SBD20 (20% simarouba biodiesel+80% diesel) and SBD30 (30% simarouba biodiesel+70% diesel) with injection timing of 23° btdc and injection pressure of 200 bar. The results of performance and emissions obtained are analyzed and compared with diesel. The experimental chart consisting of full factorial design with 12 experiments on conventional engine is presented in table 3.



Figure 2. Engine test rig with gas analyzer and smoke meter.

Table 2. Test engine specifications.

Kirloskar Engine (TAF 1) 4-stroke, Air cooled, Single cylinder	
Rated Power	4.4 kW at 1500 rpm
Bore (D) x Stroke (L)	87.5 mm x 110 mm
Compression ratio	17.5:1
Cubic capacity	0.662 lt.
Injection timing	23° bTDC
Injection pressure	200 bar
Piston bowl	Hemi spherical



Table 3. Experimental chart along with performance and emission characteristics.

Run Order	BP- kW	Blend -%	BTE -%	BSFC -kg/ kW-h	HC - ppm	CO - Vol. %	NO _x - ppm	FSN
1	1.17	10	16.5	0.5022	67	0.02	391	0.01
2	2.29	10	22.66	0.3653	72	0.03	780	0.05
3	3.38	10	23	0.3601	75	0.03	1155	0.14
4	4.36	10	22.35	0.3704	76	0.08	1181	2.33
5	1.17	20	17.7	0.4734	66	0.02	392	0.01
6	2.29	20	20.89	0.4009	70	0.01	786	0.01
7	3.38	20	25.35	0.3305	72	0	1043	0.02
8	4.36	20	24.12	0.3474	76	0.02	1243	0.81
9	1.17	30	17.11	0.4954	70	0.02	381	0.05
10	2.29	30	20	0.3468	71	0.02	740	0.1
11	3.38	30	24.6	0.2634	72	0.03	1109	0.11
12	4.36	30	22.71	0.3735	72	0.08	1237	2.18

3. Desirability Approach

In the present research work, desirability approach based on RSM is used for the optimization of percentage of biodiesel blends and power output. The BTE, BSFC, CO, HC, NO_x and FSN are considered as measured responses. The optimization analysis is carried out using MINITAB package, where each response is transformed into a dimensionless desirability value (d) and it ranges between d=0, which suggests that the response is completely unacceptable and d=1, which suggests that the response is highly acceptable. The goal of each response can be either maximum, minimum, target, in the range and/or equal to depending on the nature of the problem. The desirability of each response can be calculated with respect to the goal of each response [8].

4. Results and Discussions

4.1. Analysis and Evaluation of Models

Models stability is validated using Analysis of Variance (ANOVA). To verify stability of models, numerical information about p value is provided by ANOVA. Based on ANOVA, models of the present study are found to be significant as the value of p is less than 0.05, which is chosen as the reference limit. The regression statistics goodness of fit (R²) and the goodness of prediction (Adjusted R²) are shown in Table 4 for all the responses of conventional engine. The R² value indicates the total variability of response after considering the significant factors. The (Adjusted R²) value accounts for the number of predictors in the model. Both the values indicate that, the model fits the data very well.

Equations (1)–(6) represent statistical models of conventional engine with percentage blend and BP as input parameters

$$BTE = 6.87260 + 0.31279 \times A + 7.80630 \times B - 0.00899 \times A^2 - 1.11078 \times B^2 - 0.01628 \times A \times B \quad (1)$$

$$BSFC = 0.725204 - 0.003330 \times A - 0.207291 \times B + 0.000062 \times A^2 + 0.030070 \times B^2 + 0.000120 \times A \times B \quad (2)$$

$$CO = 0.147845 - 0.010751 \times A - 0.20729 \times B + 0.000062 \times A^2 + 0.030070 \times B^2 + 0.000045 \times A \times B \quad (3)$$

$$HC = 61.6913 - 0.1082 \times A + 6.0427 \times B + 0.0087 \times A^2 - 0.1087 \times B^2 - 0.1087 \times A \times B \quad (4)$$

$$NO_x = -106.870 - 5.19 \times A + 522.932 \times B + 0.058 \times A^2 - 49.487 \times B^2 + 0.856 \times A \times B \quad (5)$$

$$FSN = 2.81 - 0.4099 \times A - 7.4199 \times B + 0.0075 \times A^2 + 2.994 \times B^2 - 0.1125 \times A \times B \quad (6)$$

A – Blend (%), B – Brake Power (kW)

Table 4. RSM model evaluation for engine running with biodiesel blends.

Model	BTE	BSFC	CO	HC	NO _x	FSN
	(%)	(Kg / kW-h)	(%)	(ppm)	(ppm)	
Mean	21.41	0.386	0.03	71.58	869.83	2.81
R ²	93.02	90.2	80.15	81.74	99.23	98.50
Model Degree	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic
AdjustedR ²	87.20	82.04	79.60	78.69	98.60	97.26

4.2. Brake Thermal Efficiency (BTE)

Figure 3 shows the variation of BTE with BP for diesel and simarouba biodiesel blends. BTE increases with BP up to 75% of rated BP with all blends and then drops. BTE of SBD10 and SBD30 is lower than diesel. Marginal improvement in BTE is observed with SBD20 as it is evident from the graph. Probably this is due to the properties of the blend comparable with diesel and inbuilt small amount of oxygen present in biodiesel which enhances oxidation reactions [6]. Due to this it burns better than diesel. For other blends decrease in BTE may be due to their lower calorific value, lower volatility, higher density and higher viscosity compared to diesel [9, 10, 11].

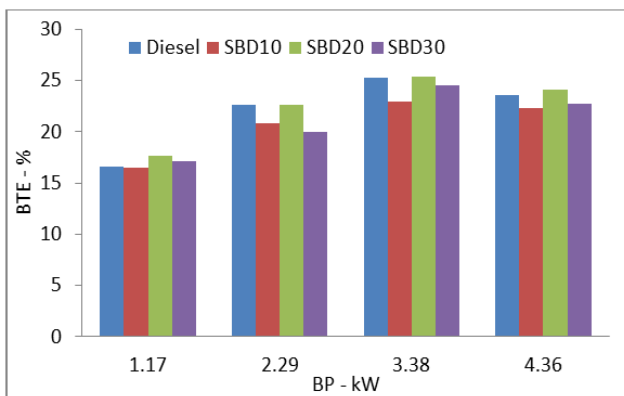


Figure 3. Variation of BTE with BP.

4.3. Brake Specific Fuel Consumption (BSFC)

Figure 4 shows variation of BSFC with BP for diesel and simarouba biodiesel blends. BSFC is higher at lower loads and is reduced at 75% of rated BP for all blends tested. BSFC increased for simarouba biodiesel blends (except SBD20) as

compared to diesel. The same is evidenced by decrease in BTE of SBD10 and SBD30. The possible reason may be lower heating value and higher viscosity of blends. SBD20 has shown slightly improved BSFC compared to diesel and is evidenced by marginal increase in BTE.

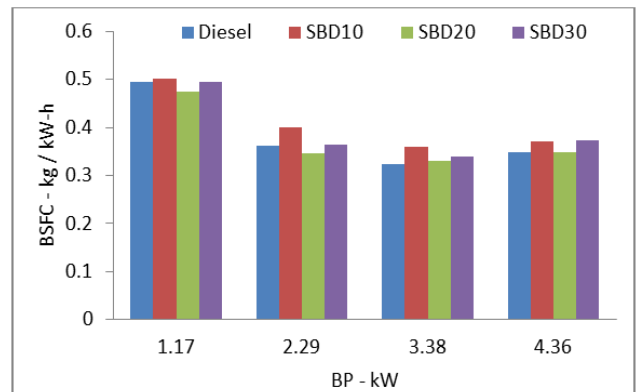


Figure 4. Variation of BSFC with BP.

4.4. Carbon Monoxide (CO) Emission

Figure 5 shows variation of CO emission with BP for diesel and simarouba biodiesel blends. CO emission is higher at lower BP and it increases with increase in BP. CO emission occurs due to oxygen deficiency during combustion of fuel and resulting in partial combustion [12, 13]. With diesel, CO formation is relatively more compared to biodiesel blends. Amongst blends used SBD20 shows lower CO emission. Reduced CO emission is an indication of improved combustion. As biodiesel is oxygenated fuel this will enhance oxidation reactions. Probably SBD20 properties are similar to diesel and presence of oxygen will aid in better combustion. The same is reported by many authors [14, 15, 16].

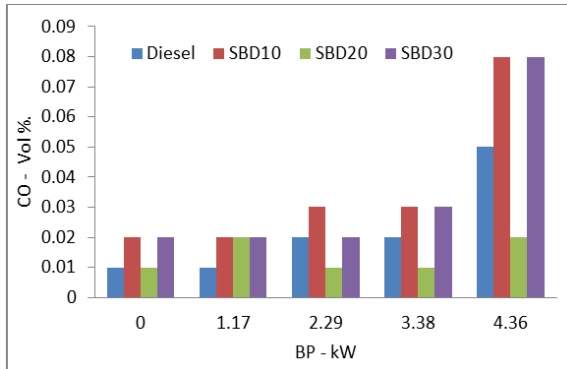


Figure 5. Variation of CO emission with BP.

4.5. Hydro Carbon (HC) Emission

Figure 6 indicates the variation of HC emission with BP for diesel and biodiesel blends. HC emission increases with increase in BP. The factors such as oxygen deficiency, wall quenching effect, excessive dilution with air etc., are responsible for formation of HC emission because of incomplete combustion [19]. As inferred from graph, HC emission decreased with SBD20 as compared to diesel. The same reasons as quoted in CO analysis are responsible for HC reduction with biodiesel blends.

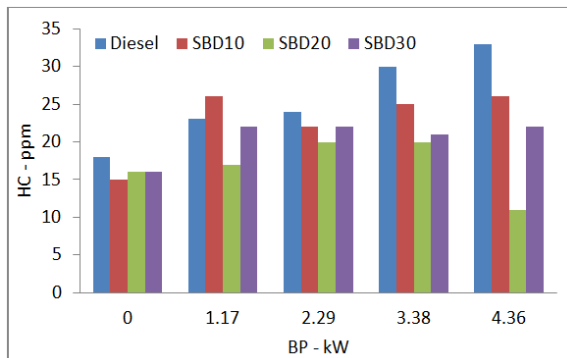


Figure 6. Variation of HC emission with BP.

4.6. Oxides of Nitrogen (NO_x) Emission

Figure 7 indicates the variation of NO_x emission with BP for diesel and biodiesel blends. NO_x emission is higher with all biodiesel blends compared to diesel. NO_x emission is increased with percentage of biodiesel in blends. This is mainly because of better burning of blends because of

inherent oxygen present in biodiesel. Better combustion results in higher in-cylinder temperature and higher NO_x.

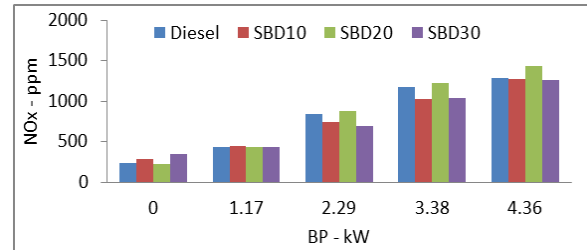


Figure 7. Variation of NO_x emission with BP.

4.7. Filter Smoke Number (FSN)

Figure 8 shows variation of FSN with BP for diesel and biodiesel blends. FSN is measure of smoke opacity which is an indication of smoke density in the exhaust emission. Higher the percentage of smoke opacity higher will be the smoke density. FSN increase with increase in BP. SBD20 has shown lower FSN at all power outputs. This is evidenced by decrease in CO and HC emission as explained.

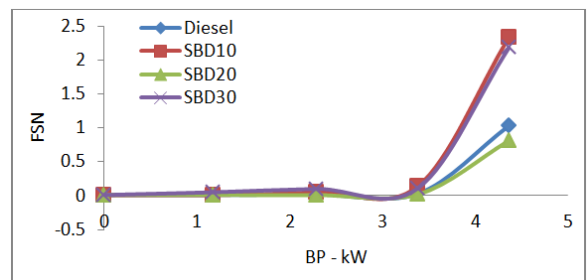


Figure 8. Variation of FSN with BP.

5. Optimization

Goal set for each response for lower and upper limits used, weight used, and importance of each factor selected for optimization criterion are presented Table 5. In the present study, amongst many best solutions obtained, the solution with optimal desirability is preferred. The RSM approach of optimization resulted in maximum optimal desirability of 0.929 with optimum blend of 21.92% and BP of 3.10 kW. These parameters can be considered as optimum for diesel engine operation having 4.4 kW of rated power at 1,500 rpm with simarouba blends as fuel.

Table 5. Optimization criterion and desirability response.

Parameter	Limits		Weight		Importance (Range 1-5)	Goal	Desirability
	Lower	Upper	Lower	Upper			
Blend (%)	10	30	1	1	3	In range	1
BP (kW)	1.17	3.36	1	1	3	In range	1
BTE (%)	16.50	25.35	0.1	1	5	Maximize	0.853
BSFC (kg/kW-h)	0.263	0.502	1	0.1	5	Minimize	0.969
CO-%	0.01	0.08	1	0.1	5	Minimize	1.000
HC- ppm	66	76	1	0.1	5	Minimize	0.915
NO _x - ppm	381	1243	1	0.1	5	Minimize	0.877
SO-%	10	42	1	0.1	5	Minimize	0.972
Optimal Desirability							0.929

6. Validation of Optimized Results

The experiments are performed thrice at optimized parameters of percentage blend and BP in order to validate the optimized responses. Average of three measured results is considered to determine actual responses. Experimental

values, predicted values and the error are shown in Table 6. The results of validation showed that the models developed are quite accurate as the percentage of error in predicted values are in a good agreement.

Table 6. Comparison of predicted and actual values.

S.No.	Value	Blend (%)	BP (kW)	BTE (%)	BSFC (kg / kW-h)	CO (%)	HC (ppm)	NO _x (ppm)	FSN
1	Predicted	21.92	3.10	24.05	0.33	0.01	71.91	1011.31	1.88
2	Actual	21.90	3.10	23.98	0.31	0.01	72.00	1014.00	1.78
3	Error	-0.02	-	-0.07	-0.02	-	0.09	2.69	0.1

7. Conclusions

Experiments are conducted on single cylinder air cooled diesel engine using simarouba biodiesel blends as substitute fuel and the following conclusions are drawn.

1. The performance of conventional engine with SBD20 showed improved BTE and BSFC compared to diesel.
2. Emissions (CO, HC and FSN) are considerably reduced with all blends tested compared to diesel
3. NO_x emission is slightly increased with biodiesel blends compared to diesel.
4. RSM approach of optimization resulted blend of 21.92% and BP of 3.1 kW as optimum values. The corresponding optimum values of responses –BTE, BSFC, CO, HC, NO_x and FSN are 24.05%, 0.33 kg/kW-h, 0.01%, 71.91 ppm, 1011.31 ppm and 1.7 respectively.

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