Performance Analysis of Diesel Engine Fueled Up with Biodiesel from Waste Vegetable Oil Using Statistical Techniques

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Abstract

The depleting resources of diesel and increasing exhaust emissions has caused damage to ozone layer and global. An alternative and renewable source of diesel is biodiesel that can help to minimize the said problems. In this research, the production of biodiesel from residual vegetable oil using the transesterification process and the analysis and side by side study of the properties and performance of different blends [B5, B10 and B15] of biodiesel and conventionally used diesel is carried out by fueling up the engine with these fuels. The objective of this research is to verify the suitability of biodiesel and different blends of it to be used in place of conventional diesel by measuring different parameters i.e., engine torque, consumption and exhaust temperature using dynamometer, graduated cylinder and calorimeter in combination, with sensor and digital display (ESSOM MT 520/502) as an output device. The acquired data for the aforementioned parameters underwent analysis employing statistical techniques. The results revealed that Blend B5 demonstrated a minimal reduction in torque, specifically less than 0.5 N, at intermediate speed levels. Additionally, it exhibited the lowest exhaust gas temperature. Conversely, Blend B15 demonstrated the most favorable fuel consumption when compared to conventional diesel. These findings contribute valuable insights into the performance characteristics of the blends, particularly in terms of torque, exhaust gas temperature, and fuel efficiency.

***Keywords**:* Bio-Diesel, Transesterification, Performance Analysis, ANOVA, Regression Analysis

Introduction

Given the pronounced depletion of resources and the escalating costs associated with diesel, the prominence of alternative fuels for diesel engines has grown significantly in importance (Fukuda et al., 2001; Ghobadian & Rahimi, 2004; Van Gerpen et al., 2007). According to the Pakistan Bureau of Statistics, the country imported around 6.37 million tons of petroleum products in the fiscal year 2020-21, out of which around 3.1 million tons were diesel (Yearbook, 2022).

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This indicates that diesel accounted for almost half of the total petroleum product imports in the country. According to Pakistan State Oil, in a time period of 1 year and 8 months i.e., From August 2021 to April 2023, the price of Hi-Cetane Diesel in Pakistan increased from 116.53/liter to 293.76/liter. It is also worth noting that the increase in the price of diesel can have a significant impact on the overall economy, as it can increase the cost of transportation and other industries that rely on diesel as a fuel source.

The significance of biodiesel lies in its role as a renewable and environmentally sustainable alternative to conventional diesel fuel. Biodiesel is a potential substitute for diesel oil (Knothe, 2010), which can be produced from waste oils, oilseed crops, and animal fats (Chandran, 2020; Goering et al., 1987), mitigating the dependency on finite fossil fuel reserves. Most vegetable oils have equivalent cetane number, calorific value, heat of vaporization, and stoichiometric air/fuel ratio with mineral diesel (Agarwal et al., 2008). Heat values decrease with increasing un-saturation as a result of fewer hydrogen. It has the potential to increase fuel supply and potentially alleviate the rising prices of traditional diesel. Moreover, biodiesel has the added benefit of being environmentally friendly and sustainable. Its production and use contribute to reduced greenhouse gas emissions and lower environmental impact compared to traditional diesel, aligning with broader goals of sustainability, and addressing climate change. In the world that increasingly values renewable energy, the role of Bio-Diesel to be used as fuel is again considered yet, a side-by-side comparison of Diesel and Bio-Diesel needs to be carried out. The comparison can be made by fueling up an engine with these fuels and then collecting important data i.e., exhaust gas temperature (The Environmental Aspect), the fuel consumption (The Economical Aspect) and Engine Torque (The Efficiency Aspect) at various speed (RPM) and loads.

Although several research studies have investigated the use of biodiesel in diesel engines, most of these studies have failed to examine and analyze the interactions of key operating parameters, such as engine torque, fuel consumption, and exhaust gas temperature, with each other and their effect on engine performance across different blends of biodiesel and conventional diesel.

This study aims to fill this gap by analyzing the aforementioned parameters and determining whether biodiesel is a viable alternative to conventional diesel. Properly analyzing these parameters is crucial to understanding the potential of biodiesel as a fuel source and determining its efficacy in replacing conventional diesel in various engine types and conditions. Therefore, this study has the potential to contribute significantly to the ongoing research and development of sustainable and environmentally friendly fuel alternatives.

Literature Study

The history of Bio-Diesel as fuel alternative in Diesel Engines extends to the 17th century (Knothe, 2010), but as soon as the supply of low cost petroleum became plentiful in the mid of 18th century the focus shifted away from vegetable oil. A shock of petroleum in 1970s caused a shift of focus again toward the use of vegetable oil as fuel (Goering et al., 1987). Many studies on biodiesel have been carried out act as a workable substitute for diesel engine (Chandran, 2020; Erdoğan et al., 2019; Khan et al., 2020). Researchers are more interested in the performance and emissions analysis of diesel engines, fueled with pure biodiesel and blends with conventional diesel oil(Bhattacharyya & Reddy, 1994; Cardone et al., 1998; De Vita et al., 1999; Laforgia & Ardito, 1995; Love et al., 2009; Moreno et al., 1999; Schumacher et al., 1992; Singh et al., 2010; Yoon et al., 2010).

The investigation by these researchers shows slight reduction of engine performance and increase in fuel consumption. The torque, power, specific fuel consumption, and emission of pollutant of both pure diesel fuel and by mixing it with blends of biodiesel is being investigated, and it's been evident that the performance and characteristics of engine is strongly affected by fuel quality. However, a substantial reduction in Sulphur oxide (SOx) emissions and considerable reduction in carbon monoxide (CO), particulate matter (PM) and visible smoke has been reported. There is an increase in Nitrogen oxides (NOx) emission due to higher temperature, which can be positively influenced by delaying the injection timing in engines (Bickel & Strebig, 2000; Elawad & Yusaf, 2004; Fukuda et al., 2001). Statistical methods have been used recently for the analysis and optimization of the operating parameters and results (Uslu & Celik, 2018; Uslu & Celik, 2020). Singh et al. (Singh et al., 2021; Singh et al., 2018) and Simsek and Uslu (Simsek & Uslu, 2020) investigated the effects of different parameters on engine performance and emissions and used RSM for optimization of these parameters. Ghobadian et al. (Ghobadian et al., 2009) and Rao et al. (Rao et al., 2017) had used artificial neural network (ANN) for non-linear mapping of input and output parameters, and predicted the engine performance and exhaust emissions quite well.

The research aims to utilize Biodiesel in internal combustion engine and study the effects on its performance. The bio-diesel produced from the waste vegetable oil utilizing a process of transesterification is used The procedure is carried out by chemical reaction of vegetable oil with monohydric alcohol in the presence of catalyst to produce mono-alkyl esters termed as Bio-Diesel (Meher et al., 2006). The production of Biodiesel from the waste vegetable oil which is unexploited in large amounts can help to address the depleting resources of diesel (any reference would be good).

The data collected is analyzed for different responses i.e., Fuel Consumption, Engine Torque and Exhaust Gas Temperature for different Bio-Diesel Blends and compared it with conventional diesel for performance analysis. A statistical approach is used for multi factors analysis for significant and non-significant parameters, defining interactions of factors and generating the corresponding multiple responses.

Materials and Method

Superior and premium Bio-Diesel is the one obtained from dry and low acidic oil. Oil which is wet and high in acidity is regarded as low quality. For a low quality, the Pre-Production Process is carried out in which a large amount of base needs to be added to first neutralize the extra acidic nature and then secondly for the reaction to occur. Thus, the amount of base added is critical for Bio-Diesel Production and depends upon the acidity of the oil used for which, a process called Titration is used. Titration is carried out by adding alcohol which has neutral pH value to a sample amount of oil in observation. Commonly used alcohol is isopropyl alcohol. Then a pH indicator usually Phenolphthalein, is added to the mixture of sample amount of oil and alcohol along with steady addition of a solution of water with small amount of base chemical which will be used for the production of Bio-Diesel. Oil filters are used for filtration of food particles and other contaminants from the oil. An oil filter of 400-600 micron is used where, 400-600 is the size of the holes in the filters. Oil is preheated to make it easier for the oil to pass out through filter. The dewatering is carried out by letting the water molecules to sink at the bottom and then get removed. (Fukuda et al., 2001)

The actual Phase of Production in which 5 liters of heated oil, 38 grams of Potassium Hydroxide (KOH) and 1 liter of Methanol are used. The process is visualized as in figure 1.

The postproduction process includes washing so that the Impurities like glycerin and methanol (3% in Un washed Bio-Diesel) needs to be extracted from the Bio-Diesel to make it pure. For the said purpose, water is used to soak up that methanol which holds and dissolves other impurities in Bio-Diesel. After removing Methanol all other impurities become isolated and are easily washed away with water. After washing, Bio-Diesel is allowed to dry to make it ready for blending (Schuchardt et al., 1998) since Pure Bio-Diesel (B100) has a heating value of 39.9 which is less than the heating value of pure Diesel (B0) i.e., 44.79 which means that more Bio-Diesel will be consumed by an engine as compared to pure Diesel for producing same amount of heat energy. Therefore, Blending the Bio-Diesel with pure Diesel is an economic option to move on (Yusoff et al., 2020).

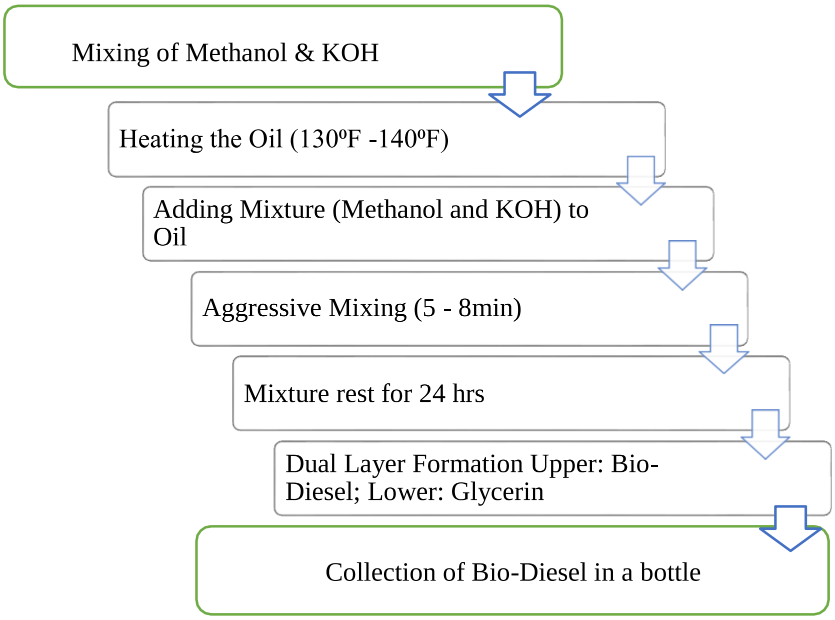

Figure 1: Bio-Diesel Processing

Bio-Diesel can be used purely or as a blend in pure diesel, designation i.e., "B" is used to state the amount of biodiesel in any fuel mix. Different Blends considered in this study are presented in Table 1.

Table 1
Blends of Bio-Diesel under study

Designation	Bio-diesel percentage
B0	0% (pure diesel)
B5	5% (95% pure diesel)
B10	6% to 10% (94% to 90% pure diesel)
B15	11% to 15% (89% to 85% pure diesel)

Experimental Setup

The apparatus used to find the properties of the fuel for comparative property study of Bio Diesel and Pure Diesel is summarized below in Table 2. While Table 3 shows the Diesel vs. Bio-Diesel Properties Comparison.

A single cylinder Diesel Engine having power of 3.7 kW, maximum speed of 8000 rpm and maximum Torque of 110 N-m at 2500 rpm, is connected to dynamometer coupled with instruments to measure torque, speed, air and fuel flow rates and temperature of exhaust gases as shown in Figure 2. Figure 3 show the Engine Parameters [Factors: Load, Rpm and Blends; Responses: Engine Torque, Engine Fuel Consumption, Exhaust Gas Temperature].

Table 2

Apparatus Used

Equipment name	Equipment model	Purpose
Viscometer	Plc/msc/rts/026	To measure viscosity of fluid (in kg/m.s)
Calorimeter	Auto bomb ca-4rt	To measure the heat of combustion (in MJ/kg)
Martens meter	Flash point pm-1	To determine the lowest ignition temperature (flash point) (in °F)
Pycnometer	Mettler toledo d40	To find out the density of liquid (in kg/m^3)

Table 3

Diesel vs. Bio-Diesel (Properties Comparison)

Properties	Diesel	Biodiesel
Density at 30°C (kg/m^3)	820	866
Kinematic viscosity at 40°C (cst)	2.87	4.67
Flash point (°F)	205	300
Calorific value (MJ/kg)	45.5	36.5

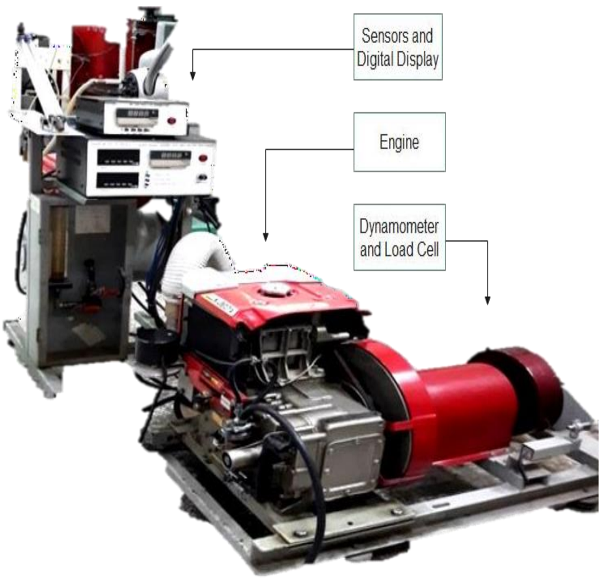

Figure 2: Engine Setup

Figure 3: Engine Parameters [Factors: Load, Rpm and Blends; Responses: Engine Torque, Engine Fuel Consumption, Exhaust Gas Temperature]

Design of Experiment

The approach used in this experiment is Full Factorial and the design of our experiment include three number of factors while the number of Responses is also three. Factors and Responses classification for this research is illustrated in Table 4.

Table 4
Factors and Responses Classification

Variable	Classification	(levels) [no of levels]
Load	Factor-1 (numeric-discrete)	(0.25, 0.5, 0.75 & 1)
Engine speed	Factor-2 (numeric-discrete)	(540, 730, 910 & 1100)
Type of fuel	Factor-3 (categoric-nominal)	(b0, b5, b10 & b15)
Engine torque	Response-1	Data collection from instruments
Engine fuel consumption	Response-2	
Exhaust gas temperature	Response-3	

In this experiment, for 3 types of factors (each having 4 levels) and 4 types of responses the number of runs set by the Design Experiment software is 64. Design Expert offer 4 different types of design studies 1) The Factorial Design, 2) The Response Surface Design, 3) The Mixture Design and 4) Custom Design. Since our data contains categoric and numerical factors and having many runs so the best option is custom design which further offers Optimal, User-Defined, Historical and Simple Sample Design Studies. Since user-defined offers all possible component and factor combinations for different runs, we opt for it to move through the Full Factorial Design. After defining/selecting the types and levels for factors and selecting responses in the software, the data table is generated for 64 runs by the software. Then for each run data collected is feed in Design Expert which is as follows:

Results and Discussion

Engine Torque

Engine torque being an important aspect of a diesel engine for which the model analysis and Analysis of Variance for Engine Torque is tabulated in Table 5. From *Table 5*

ANOVA (Engine Torque) Design Expert Output

The F-value is 1027.29, the Quadratic Model is significant and will give a better estimate for significance of factors. The P-value for B and B^2 is significant since it is less than the standard significance level (α: 0.05), therefore rejecting the Null Hypothesis. Thus, the results suggest that the Engine Torque is significantly affected by factor B i.e., engine speed and factor B^2, the quadratic term of engine speed. All other Factors are classified as non-significant. All of the interactions between factors i.e., AB, AC and BC are classified as non-significant since their P-value is less than (α: 0.05).

Table 5

ANOVA (Engine Torque) Design Expert Output

Source	**Sum of Square**	**Df**	**Mean Square**	**F-Value**	**P-Value**	
Model	4486.65	14	320.48	1027.29	< 0.0001	significant
A-Load	0.2703	1	0.2703	0.8664	0.3565	
B-Engine Speed	4380.13	1	4380.13	14040.57	< 0.0001	
C-Fuel	1.02	3	0.3389	1.09	0.3637	
AB	0.5640	1	0.5640	1.81	0.1849	
AC	2.22	3	0.7410	2.38	0.0814	
BC	2.46	3	0.8191	2.63	0.0608	
A^2	0.2377	1	0.2377	0.7618	0.3870	
B^2	99.75	1	99.75	319.75	< 0.0001	
Residual	15.29	49	0.3120			
Cor Total	4501.94	63				

Before moving towards statistical inference techniques, the validity of the assumed model must be verified. From Figure 4. Diagnostics: Plots of Residuals (Engine Torque), the validity of the model that is used by the software is justified i.e., the three assumptions for the random error term in a regression model are not violated which includes (1. The normality, 2. The Homoscedasticity and 3. Independency). The UL [Upper Left] graph which is the normal quantile-quantile plot of residuals indicates that the normality assumption is not violated since the residuals are plotted approximately normally and which results in a straight line and thus is pretty a best fit for residuals. From the rest of plots, it is concluded that the there is a random scatter of points with weak outliers at load of 1 N, engine speed of 1100 RPM and for fuel blend B5 which are not sufficient to deny model assumptions thus the assumption of linearity and constant variance (Homoscedasticity) holds valid and it does not contradict the assumed model.

From Figure 5. Model Graphs; 3D Surface Output (Engine Torque) [UL: B0; UR: B5; LL: B10; LR: B15] [UL: Upper Left; UR: Upper Right; LL: Lower Left; LR: Lower Right], it is obvious from the contours on the base of each surface graph that at maximum level of load and speed, B5 offers exceptionally larger amount of torque than any other blend and diesel. Also, the statement is true for a minimum level of speed and any level of load. The average trend of contour for blend B5 is upwards thus for high torque output B5 blend is recommended. Also, from Table 5

ANOVA (Engine Torque) Design Expert Output, the significant factor is B i.e., for Engine Speed the maximum response output for Torque is by fueling up with Fuel Blend B5. Thus, the factor of key importance for the response of Torque is Engine Speed for which B5 is the best choice. It is also concluded that at any level of speed, increasing the load will cause a negligible change in torque except for the maximum limits said factors which is also obvious from the ANOVA for the response (Torque). Also, the change of type of blend may not result in a large amount of change in torque as the factor significance of type of fuel on torque is stated as insignificant by the ANOVA.

Engine Fuel Consumption

The model analysis and Analysis of Variance for Engine Fuel Consumption is tabulated in Table 6. From Table 6, *ANOVA (Engine Fuel Consumption) Design Expert Output*, the F- value is 47.32, the Quadratic Model is significant and will give a better estimate for significance of factors. The P-value for B and B^2 is significant since it is less than the standard significance level (α: 0.05), thus rejecting the Null Hypothesis and so will have a significant difference in the said factors on the Engine Fuel Consumption. All other Factors are classified as non-significant. The interaction AC has P-Value less than 0.05 thus making it significant and thus rejecting Null Hypothesis and will have a significant effect on the Engine Fuel Consumption. Interactions AB and BC are classified as non-significant since their P-value is less than (α: 0.05).

Again, the validity of assumptions for the model for the response of engine fuel consumption needs to be verified before depicting anything from the statistical graphs. From Figure 6. Diagnostics: Plots of Residuals (Engine Fuel Consumption) , we can see that UL plot represents a normal distribution of residuals and from the rest of plots it is clear that there is a constant variance, so the assumed model is valid, and the assumptions are not denied. Also, at 0.5 N load, 750 RPM engine speed and for fuel B0 there is a very weak outlier which do not cause any violation for the assumed model.

From Figure 7; Model Graphs; 3D Surface Output (Engine Fuel Consumption) [UL: B0; UR: B5; LL: B10; LR: B15], it is obvious from the contours on the base of each surface graph that Blend B15 offers the least fuel consumption.

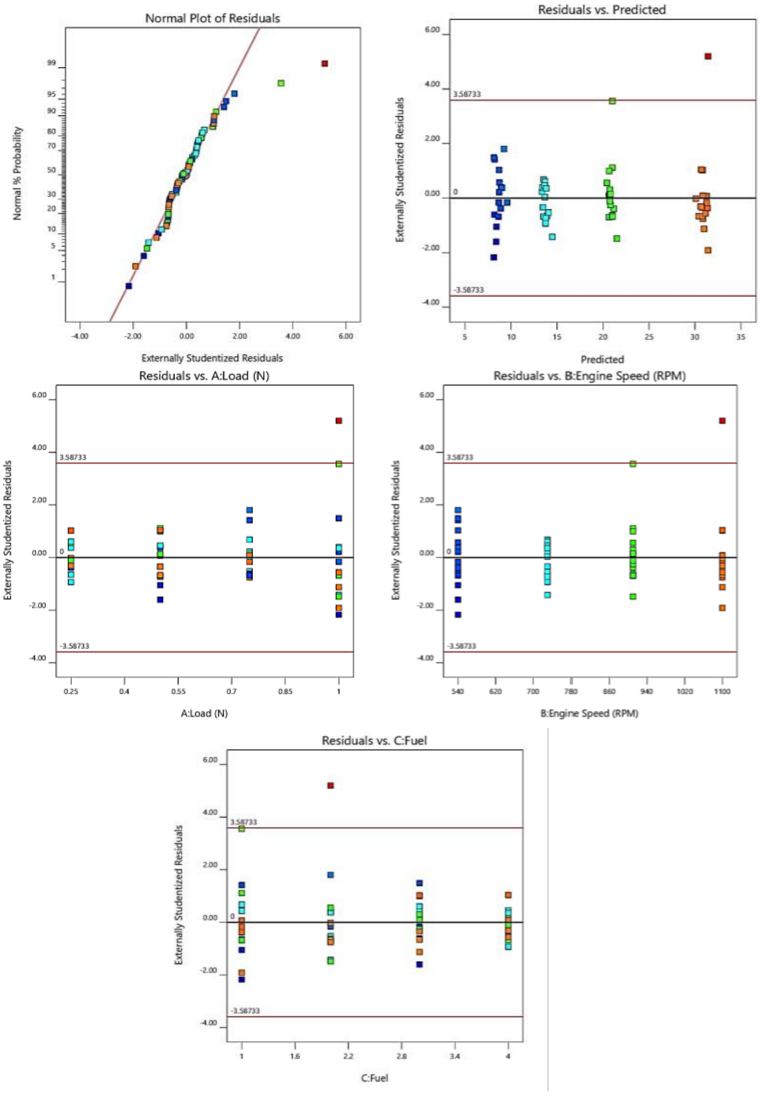

Figure 4. Diagnostics: Plots of Residuals (Engine Torque)

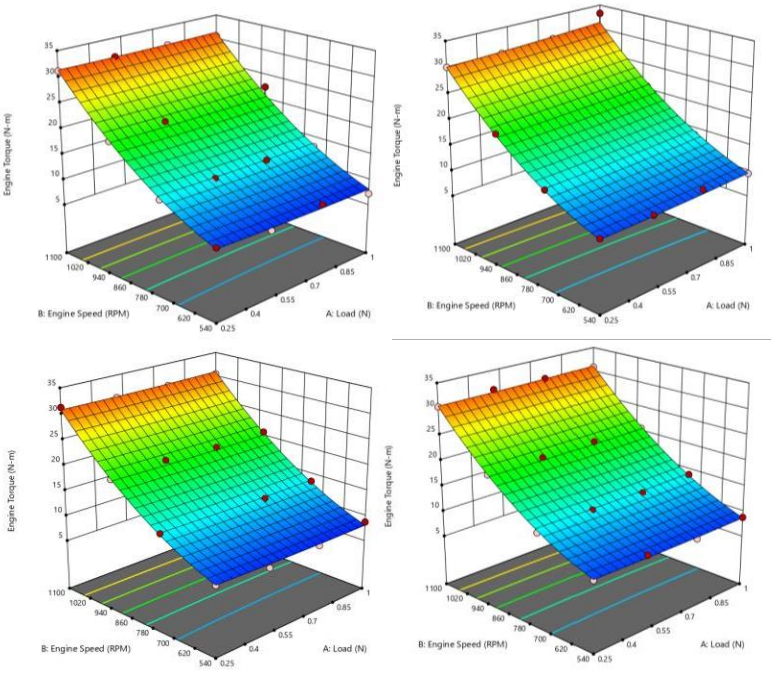

Figure 5. Model Graphs; 3D Surface Output (Engine Torque) [UL: B0; UR: B5; LL: B10; LR: B15]

Table 6
ANOVA (Engine Fuel Consumption) Design Expert Output

Source	**Sum of squares**	**Df**	**Mean square**	**F-value**	**P-value**	
Model	3.919e-07	14	2.800e-08	47.32	< 0.0001	Significant
A-load	1.262e-09	1	1.262e-09	2.13	0.1505	
B-engine speed	3.523e-07	1	3.523e-07	595.39	< 0.0001	
C-fuel	4.887e-09	3	1.629e-09	2.75	0.0524	
Ab	4.010e-11	1	4.010e-11	0.0678	0.7957	
Ac	5.706e-09	3	1.902e-09	3.21	0.0308	
Bc	6.571e-10	3	2.190e-10	0.3702	0.7748	
A^2	1.482e-10	1	1.482e-10	0.2504	0.6190	
B^2	2.697e-08	1	2.697e-08	45.58	< 0.0001	
Residual	2.899e-08	49	5.917e-10			
Cor total	4.209e-07	63				

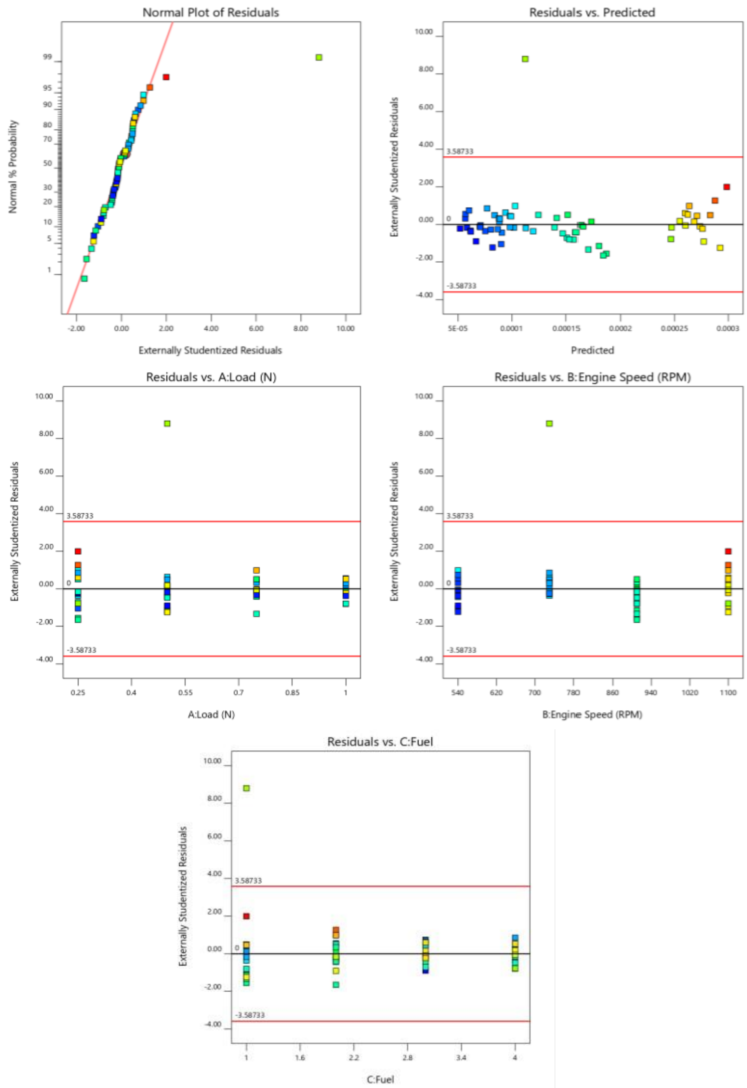

Figure 6. Diagnostics: Plots of Residuals (Engine Fuel Consumption)

The average trend of contour for blend B15 is downwards thus for low engine fuel consumption B15 blend is recommended. As in case of Torque response, the significant factor is again Engine Speed for the response of fuel consumption and the contours indicate that increasing engine speed will increase the engine fuel consumption at any level of load. Also, the factor of type of fuel is more on the significant side. Same is true for increasing load at any level of speed but the effect is negligible as indicated by the ANOVA for the factor (Load). But the effect of changing levels of speed and load causes a negligible change in the engine fuel consumption as indicated by the ANOVA for the response of engine fuel consumption.

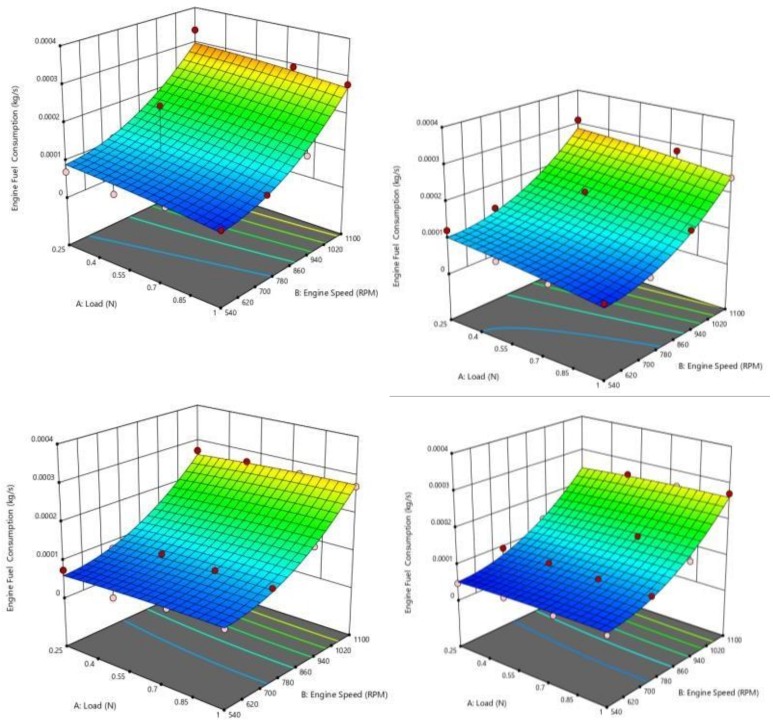

Figure 7. Model Graphs; 3D Surface Output (Engine Fuel Consumption) [UL: B0; UR: B5; LL: B10; LR: B15]

Table 7
ANOVA (Exhaust Gas Temperature) Design Expert Output

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.494E+05	27	9235.48	228.27	< 0.0001	significant
A-Load	2737.80	1	2737.80	67.67	< 0.0001	
B-Engine Speed	2.098E+05	1	2.098E+05	5186.39	< 0.0001	
C-Fuel	4961.31	3	1653.77	40.88	< 0.0001	
AB	1412.14	1	1412.14	34.90	< 0.0001	
AC	1205.73	3	401.91	9.93	< 0.0001	
BC	1975.63	3	658.54	16.28	< 0.0001	
A^2	1980.25	1	1980.25	48.94	< 0.0001	
B^2	22575.06	1	22575.06	557.97	< 0.0001	
ABC	342.57	3	114.19	2.82	0.0525	
A^2B	1116.02	1	1116.02	27.58	< 0.0001	
A^2C	816.38	3	272.13	6.73	0.0010	
AB^2	36.45	1	36.45	0.9009	0.3489	
B^2C	235.56	3	78.52	1.94	0.1404	
A^3	30.01	1	30.01	0.7418	0.3948	
B^3	96.69	1	96.69	2.39	0.1309	
Residual	1456.53	36	40.46			
Cor Total	2.508E+05	63				

However, changing the type of blend and load both has a significant effect on engine fuel consumption as indicated by the ANOVA so, for different levels of load and fuel type the least fuel consumption is for B15.

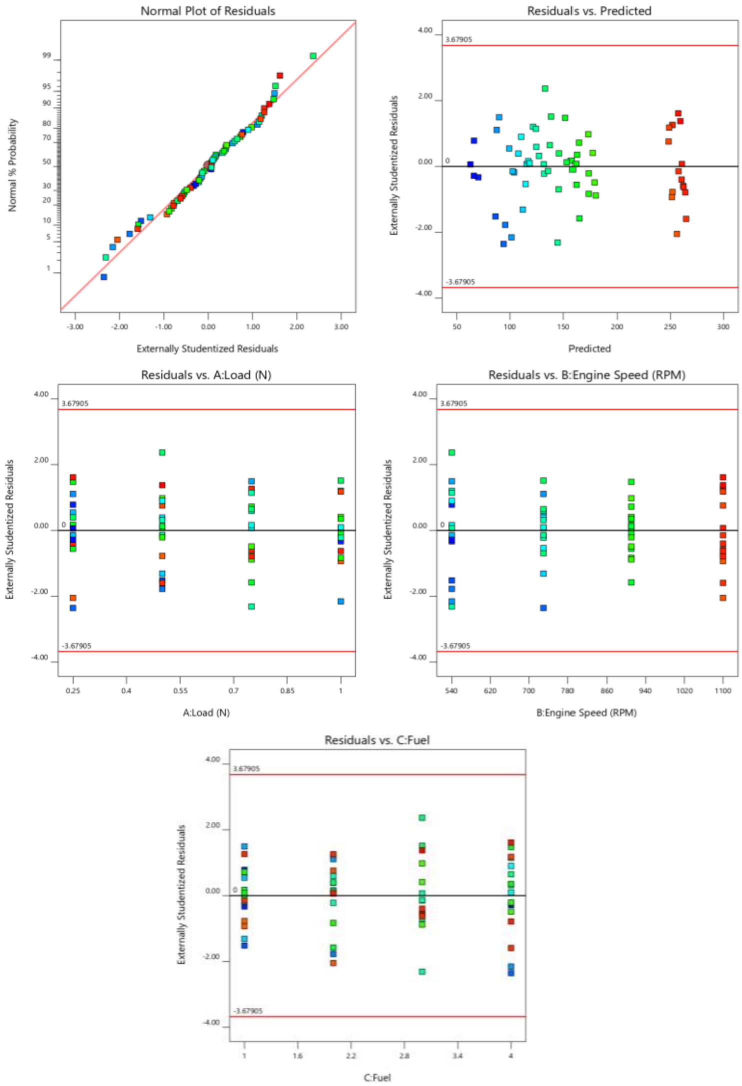

Figure 8. Diagnostics: Plots of Residuals (Exhaust Gas Temperature)

Exhaust Gas Temperature

The model analysis and Analysis of Variance for Exhaust Gas Temperature is tabulated in Table 7. From Table 7, ANOVA (Exhaust Gas Temperature) Design Expert Output, the F- value is 228.27, the Cubic Model is significant and will give a better estimate for significance of factors. The P-value for A, B, C, A^2 and B^2 is significant since it is less than the standard significance level (α: 0.05), thus rejecting the Null Hypothesis and so will have a significant difference in the said factor on the Exhaust Gas Temperature of Engine. All other Factors are classified as Non-Significant. The interactions AB, AC, BC, A^2B, A^2C have P-Values less than 0.05 thus making the said factors significant and will have a significant difference in the said factors on the Exhaust Gas Temperature of Engine. All other interactions are Non-Significant since their P-value is less than (α: 0.05).

For the model used to analyze the third response i.e., exhaust gas temperature of the study, from Figure 8. Diagnostics: Plots of Residuals (Exhaust Gas Temperature) the validity of assumptions for the model for the response of exhaust gas temperature is valid since there is constant variance and the plotted points are normally distributed (UL Graph) without any outliers.

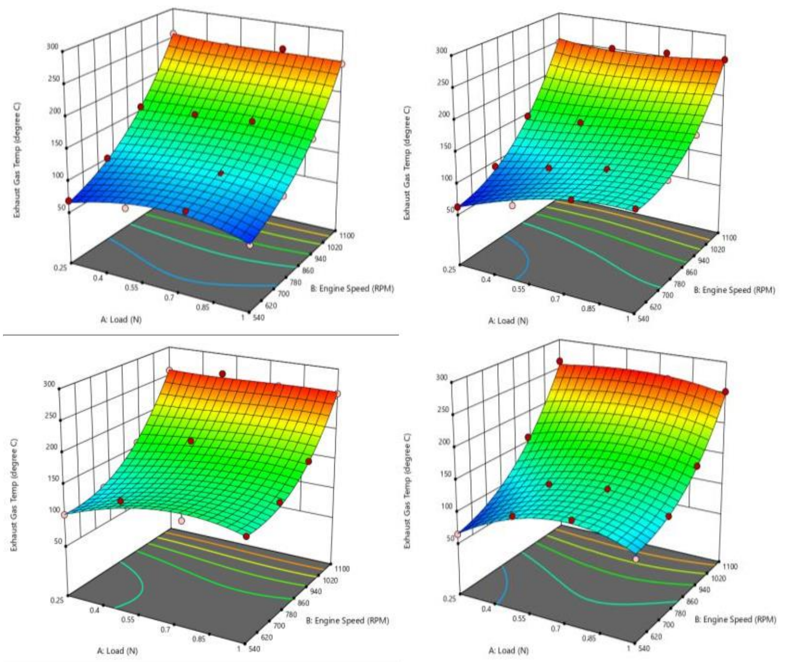

Figure 9. Model Graphs; 3D Surface Output (Exhaust Gas Temp) [UL: B0; UR: B5; LL: B10; LR: B15]

From Figure 9. Model Graphs; 3D Surface Output (Exhaust Gas Temp) [UL: B0; UR: B5; LL: B10; LR: B15], it is concluded that the contours for blend B10 are trending higher than any other blend or diesel and are nowhere in comparison with the rest of fuels and so is discarded. Also, the best fuel for the least exhaust temperature is pure diesel i.e., B0 and the blend that can best compete with it is B5. From the contours B5 can beat B0 when the load is intermediate or less than 0.5 N at any level of speed however, for higher loads B0 is recommended for use even at low speeds to get the least temperature at exhaust. As, from Table 7

ANOVA (Exhaust Gas Temperature) Design Expert Output, all factors and interactions have a strong influence on the response of exhaust gas temperature, therefore the changes in the response from any factor/factor interaction are considered large and so considered.

Conclusions

1. Bio-Diesel can be the best replacement for conventional Diesel, as the chemical properties of Bio-Diesel are similar to Diesel.
2. The transesterification process used to extract Bio-Diesel from residual vegetable oil of restaurants, homes and hotels can be used as alternative fuel to diesel.
3. The assumed models for different engine responses are valid for interpreting the results.
4. For all responses considered in the study, engine speed was identified as an important factor, as Engine Torque, Engine Fuel Consumption, Exhaust Gas Temperature vary according to engine speed.
5. The type of fuel, whether diesel or biodiesel, was found to have a negligible effect on engine torque output, suggesting that both fuels produce similar torque outputs, with F-value of 1.09 and P-value of 0.3637.
6. Blend B5 is recommended for use due to its slight, yet comparatively improved torque output, i.e., 34 N-m at 1100 rpm at full load.
7. For maximum load and speed of an engine B5 can offer comparatively larger torques.
8. For the response of torque, the factor of consideration recommended by statistical technique is Engine speed, which upon increase also cause an increase in torque.
9. For engine fuel consumption, changing speed and load does not have a significance effect on engine fuel consumption however, changing type of fuel or fuel and load causes a significance effect for which the least fuel consumption was for B15 thus, recommended for use, , i.e., 0.28×10^{-3} at 1100 rpm at full load.
10. For exhaust gas temperature, all of the factors and interactions were stated as significant and the fuel which resulted in least temperature is pure diesel. A comparable blend against diesel is B5 which resulted in even lower exhaust gas temperatures than B0 at intermediate levels of load or less than 0.5 N of load at any level of speed.

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