International Journal of Automotive & Transportation Engineering (2025) Vol 2, 155-169

SCHOLAR PUBLISHING

International Journal of Automotive & Transportation Engineering
ISSN: 3083-9726

Journal Homepage: https://e-journal.scholar-publishing.org/index.php/ijate

Optimization of Additive-Diesel Blends Using RSM on Engine Performance and Emission Characteristics

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Abstract
This study investigates the effects of various additive-diesel fuel blends and operating conditions on engine performance, combustion characteristics, and exhaust emissions of a single-cylinder, four-stroke, direct-injection Yanmar TF120M diesel engine. Utilizing Response Surface Methodology (RSM) with Central Composite Design (CCD), 65 experimental runs were conducted to develop empirical models and analyze the significance of input factors such as engine speed, load, and fuel type. The selected output responses include Brake Power (BP), Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), Exhaust Gas Temperature (EGT), and emissions (CO, CO_2, NOx). ANOVA results confirmed that all models were statistically significant with p-values < 0.0001 and high R^2 values ranging from 0.8177 to 0.9949, indicating strong model reliability. The maximum improvement in BP ranged from 3.1% to 8.1% compared to pure diesel. The best BTE reached up to 35% for blends like TD and APD, showing a 6.1% enhancement over diesel. BSFC was significantly reduced by 4.3–12.8% across various blends, with APD showing the lowest consumption at 102 g/kWh. EGT was also notably affected, with a maximum reduction of 20.8% when using OAPD, indicating improved combustion efficiency. Overall, the additive-diesel blends demonstrated improved engine performance and reduced emissions, highlighting their potential as alternative fuels. The developed models are suitable for optimizing operating conditions to achieve better efficiency and environmental performance in small diesel engines.

Article Info
Received: 06 April 2025
Revised: 15 June 2025
Accepted: 26 June 2025
Available online: 15 August 2025

Keywords
Additive-Diesel Blends
Engine Performance
Response Surface Methodology
Combustion Characteristics
Emission Reduction

Introduction

The increasing demand for energy, particularly in the transportation and industrial sectors, has intensified the global dependence on fossil fuels, especially diesel. However, the combustion of diesel fuel contributes significantly to environmental issues such as greenhouse gas emissions, particulate

matter, and nitrogen oxides (NOx). This situation has prompted extensive research into alternative fuels and fuel additives aimed at reducing environmental impact while maintaining or enhancing engine performance [1–4]. Oxygenated fuels have gained attention due to their potential to improve combustion efficiency and reduce harmful emissions. Additives such as turpentine and alpha-pinene, which are derived from natural sources, have been explored for blending with diesel to enhance its combustion characteristics. Blending turpentine with diesel increases the oxygen content of the fuel, which facilitates better atomization and combustion, thereby reducing CO and HC emissions [5–8].
Several studies have shown that adding oxygenated compounds to diesel fuel positively influences engine thermal efficiency. The addition of alpha-pinene improved brake thermal efficiency (BTE) and reduced brake specific fuel consumption (BSFC) [9–12]. Similarly, Imdadul et al. (2016) concluded that turpentine-diesel blends improved brake power (BP) due to enhanced evaporation characteristics and better fuel–air mixing, despite the additive's lower cetane number. Furthermore, exhaust gas temperature (EGT), which reflects combustion intensity, has been shown to decrease with the use of oxygenated diesel blends. Lower EGT indicates more complete combustion and less heat loss, which is desirable for engine efficiency. The use of biodiesel blends with oxygenated compounds led to reductions in EGT and NOx emissions, supporting the feasibility of such additives in emission control strategies [13–16].
Despite these advantages, the interactive effects of fuel blends, engine loads, and engine speeds require thorough investigation to optimize performance outcomes. Response Surface Methodology (RSM) provides a powerful statistical approach to evaluate such multivariate systems. RSM has been utilized to model and predict engine behavior with high accuracy, validating the technique's suitability for fuel optimization studies [17–20]. Based on this context, the present study employs RSM using a Central Composite Design (CCD) to evaluate the effects of additive-diesel blends—specifically turpentine-diesel (TD), oxygenated turpentine-diesel (OTD), alpha-pinene-diesel (APD), and oxygenated alpha-pinene-diesel (OAPD) on engine performance, combustion, and emissions. Through 65 experimental runs, this research aims to develop predictive models, identify significant factors, and assess the feasibility of these bio-additive blends as cleaner alternatives to conventional diesel fuel.
The specific objective of this study is to evaluate and optimize the impact of various additive-diesel fuel blends namely turpentine-diesel (TD), oxygenated turpentine-diesel (OTD), alpha-pinene-diesel (APD), and oxygenated alpha-pinene-diesel (OAPD) on the performance, combustion characteristics, and exhaust emissions of a single-cylinder Yanmar TF120M diesel engine under different engine loads and speeds using Response Surface Methodology (RSM). The novelty of this research lies in its comprehensive statistical modeling approach through Central Composite Design (CCD), which enables the development of accurate quadratic regression models for nine critical response parameters, including brake power (BP), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), and major emissions (CO, CO_2, NOx). Unlike previous studies that typically evaluate single blends or fixed conditions, this work offers an integrated optimization framework that simultaneously considers multiple additive types and operational variables, leading to a deeper understanding of how natural oxygenated additives influence engine performance and environmental impact.

Methodology

In the study, optimisation was conducted using response surface methodology (RSM). Related parameters and levels were selected. The design of experiment (DOE) was decided in this step. The next step was the selection of response and input data from the experiment. These include engine speed, engine load, and test fuels as the input parameters. In this stage, the data from phase two were used as the input data: engine performance (brake power (BP), brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE)), engine combustion (maximum in-cylinder pressure (ICP) and heat release rate (HRR)), and exhaust emissions (carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOX), and exhaust gas temperature (EGT)). After that, the analysis of variance (ANOVA) and regression analysis were carried out. The compliance of several criteria of ANOVA was ensured before proceeding to the results of optimal conditions. As for the confirmation of the results of RSM, a validation experiment on engine testing was done using the optimal conditions acquired. Finally, after ensuring that the optimal conditions of engine data agreed with RSM, the study was concluded.

Preparation of test fuels

This section presents the methodology for test fuel preparation. In the first part, the procedures of bio-additive preparation are discussed. This includes the materials used, the equipment involved, and the preparation procedures. Oxidation was carried out in the preparation process, followed by the chemical compound observation for the prepared bio-additives. Then, the second part discusses the preparation of test fuels. This part also describes the materials, equipment, and procedures for the preparation. After that, the details of stability observation are discussed.

Bio-additives preparation

The bio-additives used for this study were pure turpentine oil, alpha pinene oil, oxygenated turpentine, and oxygenated alpha pinene. Pure turpentine oil and alpha pinene oil were supplied by Brataco Chemical and Sangkuriang International companies, Bandung, Indonesia. The turpentine oil used is standard material and can be purchased elsewhere. These two bio-additives were oxidised to produce another two new bio-additives, namely oxygenated turpentine and oxygenated alpha pinene using reflux method. The materials, equipment, and procedures used for the oxidation process are described as follows.

Materials and equipment

The materials used for bio-additive preparation are pure turpentine oil and alpha pinene oil. These materials and oxygen (O2) gas were supplied by Brataco Chemical and Sangkuriang International companies, Bandung, Indonesia. Pure turpentine oil and alpha pinene oil were oxygenated by the oxidation process using reflux method. The apparatuses used included a thermometer, a condenser, a controllable heater as a regulator, a cylinder column, glass, a pressure gauge, and a barometer. The setup of this process is presented in **Figure 1**.

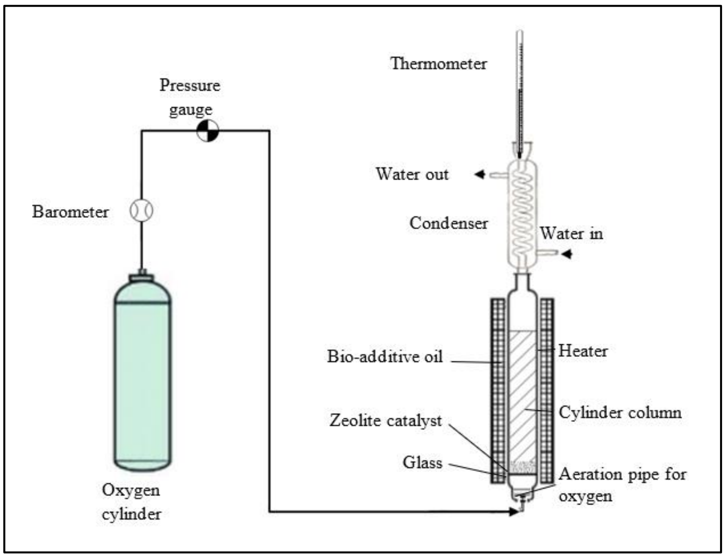

Figure 1: Oxidation process setup

Bio-additive preparation procedures

The oxidation procedure was carried out by reflux method. The reflux method used was in reference to Hung and co-workers [21] and followed the standard procedure for heating with reflux. This method used a cylindrical column reactor with a length and diameter of 30 cm and 2 cm, respectively. About 15 mL of bio-additive was aerated (the process of introducing air into a substance) with O2 at a flow rate of 3 L/min and heated using an electrical wire heater at a temperature range of 90–100 °C for 3 h, as shown in **Figure 1**. The oxidation procedure was conducted at the Life Science Laboratory, Department of Chemistry, Indonesia University of Education, Bandung, Indonesia.

Bio-additive chemical compound observation

The chemical compound of the produced bio-additives was observed using chromatography. For the testing, gas chromatography-mass spectrometry (GC-MS, Shimadzu model QP5050A and GC-17A) was used to determine the chemical compositions of turpentine oil before and after oxidation. The GC-MS analysis was carried out with helium as the carrier gas at 120 kPA and 145 L/s (5.0 mL/min) at an initial flow rate of 1.0 mL/min. The GC-MS used a turbomolecular pump and ceramic bearing. It was equipped with an analytical capillary column with model DB-624 capable of reaching a maximum temperature of 200 °C (60.0 m length, 0.018 mm film thickness, 0.32 mm diameter). The oven temperature was first set at 40 °C for 2 min before being increased to 200 °C with a 2-min equilibrium time.

Bio-additives-diesel blending preparation

In this study, five test fuels were used: diesel (D), turpentine-diesel blend (TD), alpha pinene-diesel blend (APD), oxygenated turpentine-diesel blend (OTD), and oxygenated alpha pinene-diesel blend (OAPD). As for diesel, pure diesel Euro2M was used, which was supplied by Rahar Jati Sdn. Bhd., a commercial company located in Kuantan, Pahang, Malaysia. Another four test fuels were bio-additives blended with diesel. Pure turpentine oil and alpha pinene oil were supplied by Brataco Chemical, Bandung, Indonesia. Meanwhile, oxygenated bio-additives were produced at the Life Science Laboratory, Department of Chemistry, Indonesia University of Education, Bandung, Indonesia. The blending process was conducted in the Engine Laboratory, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Pekan, Pahang, Malaysia. The blending materials, equipment, and procedures used are described as follows.

Result & Discussion

Analysis of response surface methodology

In this subchapter, the effect of input factors (fuel mixes and engine loads) on engine performance, combustion, and exhaust emissions was investigated based on the central composite design (CCD) of response surface methodology (RSM). The goal is to develop regression models that show how employing additive-diesel blends affects the performance, combustion, and emissions of a single-cylinder, four-stroke, direct-injection Yanmar TF120M diesel engine. The output responses of BP, BTE, BSFC, EGT, ICP, HRR, CO_2, CO, and NOX were chosen and correlated to the input components. Based on the two input components, the plots of main and interaction effects, as well as three-dimensional (3D) surface plots, were produced. In addition, the empirical models were fitted to establish a link between the components and the result.

Analysis and model evaluation

The analysis of variance (ANOVA) was used to examine the output model responses produced from the experiment, as shown in **Table 1**. The p-value of the model that is less than 0.05 is a significant model to reflect the experiment output, according to the output response from ANOVA. Furthermore, at a 95% confidence level, a p-value of less than 0.05 implies that the factors have a significant effect. The regression coefficient (R2) values, on the other hand, are near to 1 and have a reasonable agreement with Adj. R2 value, which implies that the responses are desirable. The model types with the lowest standard deviation (σ) are the most accurate. All the output responses were best fitted with quadratic models, according to the R2 values and σ produced by the software. The adequate precision (AP) value represents the signal-to-noise ratio. As all responses indicate that an AP value greater than 4 is desirable, the model shows a sufficient indication that it may be used to explore the design space.

Table 1: ANOVA statistical analysis for output responses

Responses	BP	BTE	BSFC	EGT
P	< 0.0001	< 0.0001	< 0.0001	< 0.0001
F	538.46	58.86	44.99	164.92
R^2	0.9949	0.9551	0.9421	0.9835
Adj R^2	0.9930	0.9389	0.9212	0.9775
AP	94.594	29.255	25.910	57.972

Interaction effect of test fuels, engine speeds, and engine loads

Brake Power analysis

The ANOVA data of the BP of test fuels at various engine speeds and loads are presented in **Table 2**. This model has an F-value of 538.46 and a p-value of lower than 0.0001, which is less than 0.05, indicating that the model is significant. The R2 value is also 99.5%, indicating a difference of less than 0.005 between the Pred R-Squared (98.9%) and the Adj R-Squared (99.3%). Engine speed is a significant term in the ANOVA table, but the fuel and the engine loads have smaller effects, as described by the sum of squares. This is agreed with the given BP equation. **Eq.1** describes the relationship between BP and engine speed (A), engine load (B), and fuels (C), where C1, C2, C3, C4, and C5 are D, TD, OTD, APD, and OAPD, respectively.

Table 2: Analysis of variance table for BP

Source	Sum of Squares	df	Mean Square	*F*-Value	*p*-Value Prob > *F*	
Model	205.47	17	12.09	538.46	<0.0001	significant
A-Speed	151.16	1	151.16	6,734.25	<0.0001	
B-Load	47.28	1	47.28	2,106.22	<0.0001	
C-Fuel	0.74	4	0.19	8.26	<0.0001	
AB	2.02	1	2.02	89.82	<0.0001	
AC	0.14	4	0.034	1.52	0.2106	
BC	0.34	4	0.085	3.78	0.0096	
BC	0.34	4	0.085	3.78	0.0096	
A^2	1.89	1	1.89	84.01	<0.0001	
B^2	0.57	1	0.57	25.48	<0.0001	
Residual	1.05	47	0.022			
Lack of Fit	0.96	27	0.036	7.52	<0.0001	significant
Pure Error	0.095	20	4.728E-003			
Cor Total	206.52	64				

R-Squared sum of squares 0.9949
Adj R-Squared sum of squares 0.9930
Pred R-Squared sum of squares 0.9887

$$BP = 6.93 + 2.24A + 1.26B - 0.14C_1 - 6.308E - 003C_2 + 0.18C_3 - 0.069C_4 + 0.32AB - 0.11AC_1 + 0.050AC_2 + 0.077AC_3 - 0.048AC_4 - 0.077BC_1 + 0.055BC_2 + 0.090BC_3 - 0.17BC_4 - 0.37A^2 - 0.20B^2 \quad (1)$$

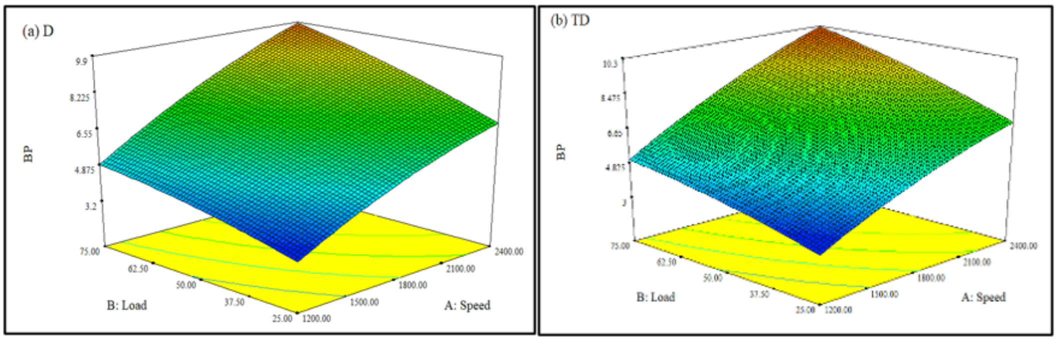

Figure 2: Response surface plots for BP variation in test fuels of (a) D, (b) TD, (c) OTD, (d) APD, and (e) OAPD

The 3D surface plots of the quadratic model for engine BP for various fuel blends and engine loads are shown in **Figure 2** (a-e). The BP increased as the engine load increased for all fuel mixes, as presented in the contour plots. Furthermore, as demonstrated in the 3D plots, the BP also increased as the engine speed increased. From **Figure 2** (a-e), the figures show that the BP of D is in a range of 3.2–9.9 kW, followed by 3–10.3 kW for TD. The BP of the remaining test fuels (OTD, APD, and OAPD) is in a range of 3–10.7 kW. Hence, the improvement of BP compared to the baseline D is between 3.1% and 8.1%. Despite having a lower cetane number than diesel fuel, turpentine oil, alpha pinene oil, and oxygenated fuels have higher O_2 content, higher latent heat of evaporation, and higher calorific values [22,23]. As a result, adding these additives to mixed fuels will change both engine performance and BP output. In brief, the high O_2 content that can be used in fuel-rich places leads to good atomisation and low viscosity, resulting in improved combustion efficiency and more power generated [24].

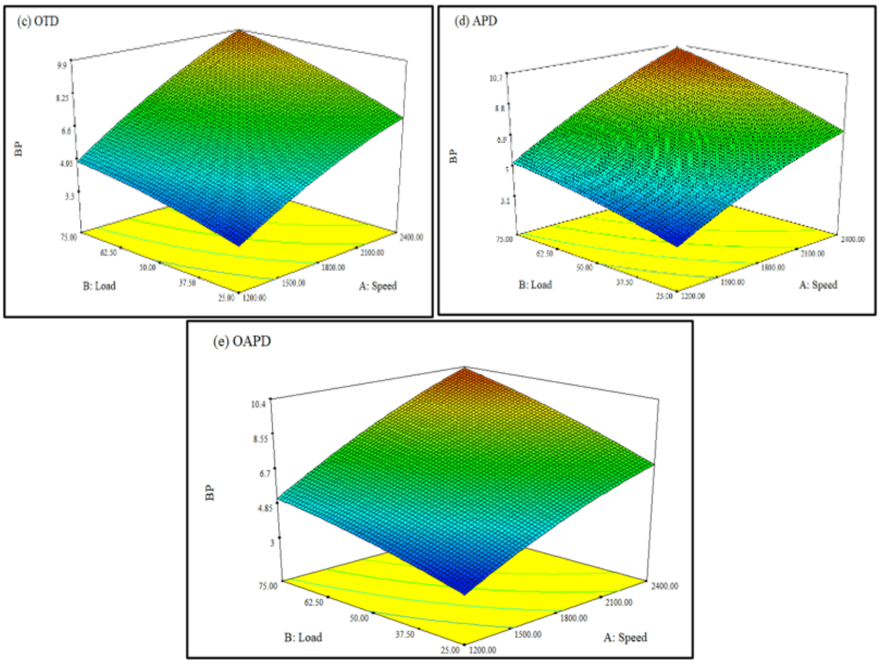

Figure 3: Continued

Brake thermal efficiency analysis

Table 3 shows the ANOVA data for the BTE of test fuels at various engine speeds and loads. The F-value for this model is 58.86, and the p-value is less than 0.0001, which is less than 0.05, suggesting that the model is significant. Similarly, the R2 value is 95.51%. The difference between the Pred R-Squared (88.77%) and the Adj R-Squared (93.89%) is less than 0.1. In the ANOVA table, engine load is a significant term, but engine speed and fuels have smaller effects, based on the sum of squares. This corresponds to the BTE equation, as shown in **Eq. 2**. This equation describes the relationship between BTE and engine speed (A), engine load (B), and fuels (C), where C1, C2, C3, C4, and C5 are D, TD, OTD, APD, and OAPD, respectively.

Table 3: Analysis of Variance Table for BTE

Source	Sum of Squares	df	Mean Square	*F*-Value	*p*-Value Prob > *F*	
Model	1,022.23	17	60.13	58.86	<0.0001	significant
A-Speed	13.02	1	13.02	12.74	0.0008	
B-Load	901.90	1	901.90	882.79	<0.0001	
C-Fuel	28.48	4	7.12	6.97	0.0002	
AB	12.32	1	12.32	12.06	0.0011	
AC	11.57	4	2.89	2.83	0.0348	
BC	6.88	4	1.72	1.68	0.1695	
A^2	2.71	1	2.71	2.65	0.1102	
B^2	46.97	1	46.97	45.97	<0.0001	
Residual	48.02	47	1.02			
Lack of Fit	48.02	27	1.78			
Pure Error	0.000	20	0.000			

R-Squared sum of squares 0.9551
Adj R-Squared sum of squares 0.9389
Pred R-Squared sum of squares 0.8877

$$BTE = 24.82 - 0.66A - 5.48B - 0.37C_1 + 1.03C_2 - 0.43C_3 - 0.74C_4 + 0.79AB - 0.33AC_1 - 0.16AC_2 - 0.60AC_3 - 0.093AC_4 + 0.14BC_1 - 0.27BC_2 - 0.79BC_3 + 0.54BC_4 - 0.44A^2 + 1.84B^2 \quad (2)$$

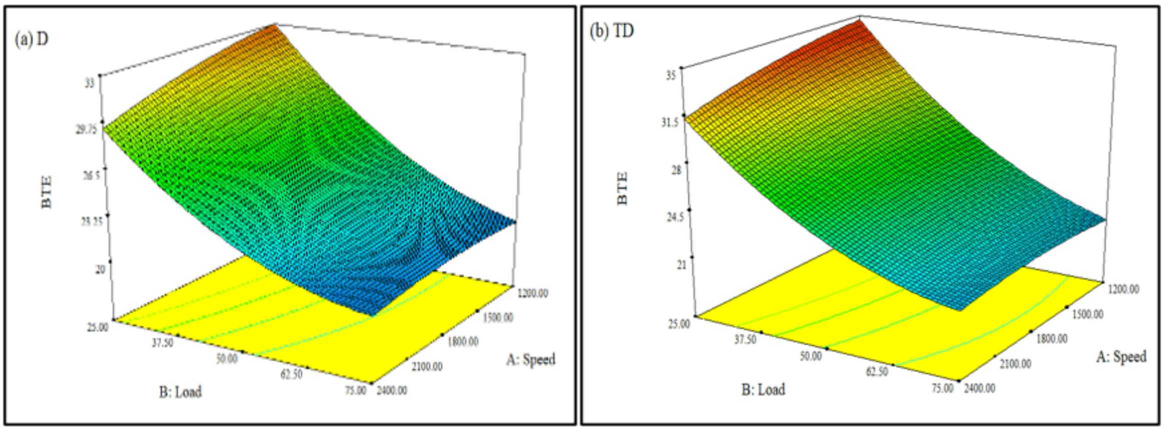

Figure 4: Response surface plots for BTE variation in test fuels of (a) D, (b) TD, (c) OTD, (d) APD, and (e) OAPD

The 3D surface plots of the quadratic model of engine BTE for various fuel blends and engine loads are shown in **Figure 4** (a-e). Based on the 3D plots, the BTE slightly improved as the engine speed increased but decreased as the engine load increased. Also, based on the contour plots, the addition of additives in fuels slightly improved the BTE up to 6.1%. As shown in **Figure 4** (a–e), the baseline BTE of D is in a range of 20–33%. Overall, APD has the minimum values of BTE with 19%, while TD and APD have the highest values of BTE with 35%. Generally, additives in fuels slightly enhance the BTE. These findings are in line with a prior study. According to Huang et al [25], adding pine chemicals to diesel-blended fuels enhanced the BTE. Furthermore, as chemical additives have a lower boiling point, density, and viscosity than D, the spray quality is increased. In addition, as the additive O_2 ratio increases, cylinder heat losses decrease, resulting in increased BTE. The increase in the BTE of chemical additives is most likely due to increasing reaction activity as the additive proportion in the blended fuel increases, resulting in a shorter CD [26].

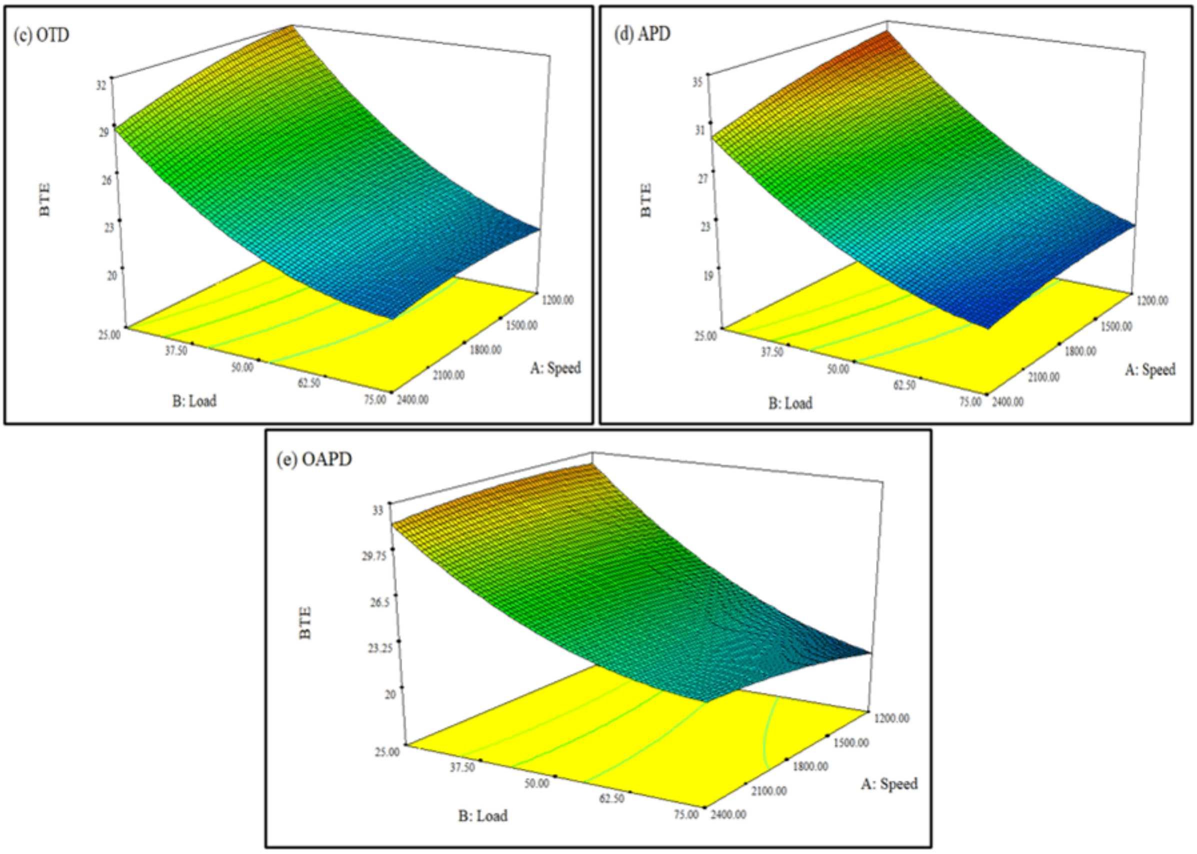

Figure 5: Continued

Brake specific fuel consumption analysis

The BSFC refers to the amount of fuel used to generate a given amount of engine BP. The ANOVA data of the BSFC of test fuels at various engine speeds and loads are shown in **Table 4**. This model has an *F*-value of 44.9 and a *p*-value of less than 0.0001, which is less than 0.05, indicating that the model is significant. The R^2 value is also 94.21%. The difference is less than 0.1 between the Pred R-Squared (85.74%) and the Adj R-Squared (92.12%). Engine load is a significant term in the ANOVA table, but engine speed and fuels have smaller effects, as stated in the sum of squares. This is in-line with the given BSFC equation. **Eq.3** describes the relationship between BSFC and engine speed (A), engine load (B), and fuels (C), where C_1, C_2, C_3, C_4, and C_5 are D, TD, OTD, APD, and OAPD, respectively.

Table 4: Analysis of variance table for BSFC

Source	Sum of Squares	df	Mean Square	*F*-Value	*p*-Value Prob > *F*	
Model	31,063.39	17	1,827.26	44.99	<0.0001	significant
A-Speed	212.96	1	212.96	5.24	0.0266	
B-Load	28,975.88	1	28,975.88	713.49	<0.0001	
C-Fuel	843.76	4	210.94	5.19	0.0015	
AB	211.45	1	211.45	5.21	0.0271	
AC	336.05	4	84.01	2.07	0.1000	
BC	210.82	4	52.71	1.30	0.2846	
A^2	151.36	1	151.36	3.73	0.0596	
B^2	220.88	1	220.88	5.44	0.0240	
Residual	1,908.75	47	40.61			
Lack of Fit	1,908.75	27	70.69	1.767E+007	<0.0001	significant
Pure Error	8.000E-005	20	4.000E-006			
Cor Total	32,972.14	64				

R-Squared sum of squares 0.9421
Adj R-Squared sum of squares 0.9212
Pred R-Squared sum of squares 0.8574

$$BSFC = 151.14 + 2.66A + 31.08B + 4.85C_1 - 4.05C_2 - 2.42C_3 - 2.17C_4 - 3.25AB + 0.55AC_1 + 0.77AC_2 + 3.96AC_3 + 0.94AC_4 + 0.60BC_1 - 0.42BC_2 + 4.72BC_3 - 2.01BC_4 + 3.31A^2 - 4.00B^2 \quad (3)$$

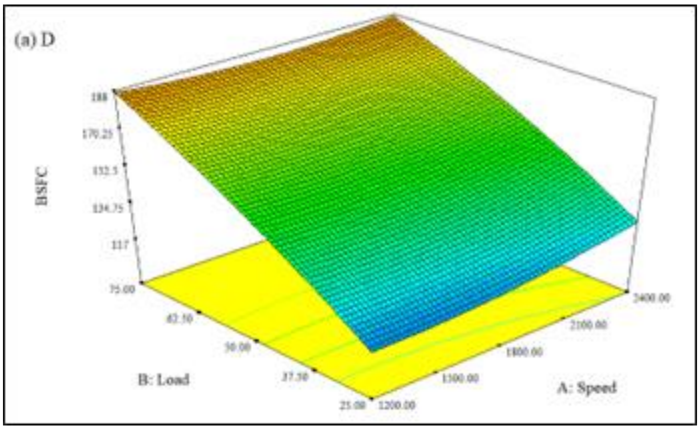

Figure 6: Response surface plots for BSFC variation in test fuels of (a) D, (b) TD, (c) OTD, (d) APD, and (e) OAPD

Figure 6 (a–e) show the 3D response surface plots for the quadratic model of engine BSFC of each fuel at various engine speeds and loads. For all fuel blends, the BSFC increased as the engine load increased, as shown by the contour maps. Furthermore, the BSFC increased slightly as the engine speed increased, as shown in the 3D plots. The minimum and maximum values of BSFC for each test fuel differ from one another. **Figure 6** (a) shows that the minimum BSFC is 117 g/kWh, while the maximum BSFC is 188 g/kWh of D at various engine speeds and loads. **Figure 6** (b–e) show the minimum values of BSFC for TD, OTD, APD, and OAPD of 109 g/kWh, 112 g/kWh, 102 g/kWh, and 122 g/kWh, respectively. From similar figures, the maximum values of BSFC are 178 g/kWh, 178 g/kWh, 188 g/kWh, and 190 g/kWh for TD, OTD, APD, and OAPD, respectively. Compared to the baseline D, it is notable that these fuels give lower BSFC in most cases, which achieved a significant improvement of 4.3–12.8%. Due to the higher heating value of turpentine and alpha pinene than diesel, these additive-diesel blends consume less fuel than pure diesel. The conclusions of this inquiry are similar to those of previous researchers [27–29].

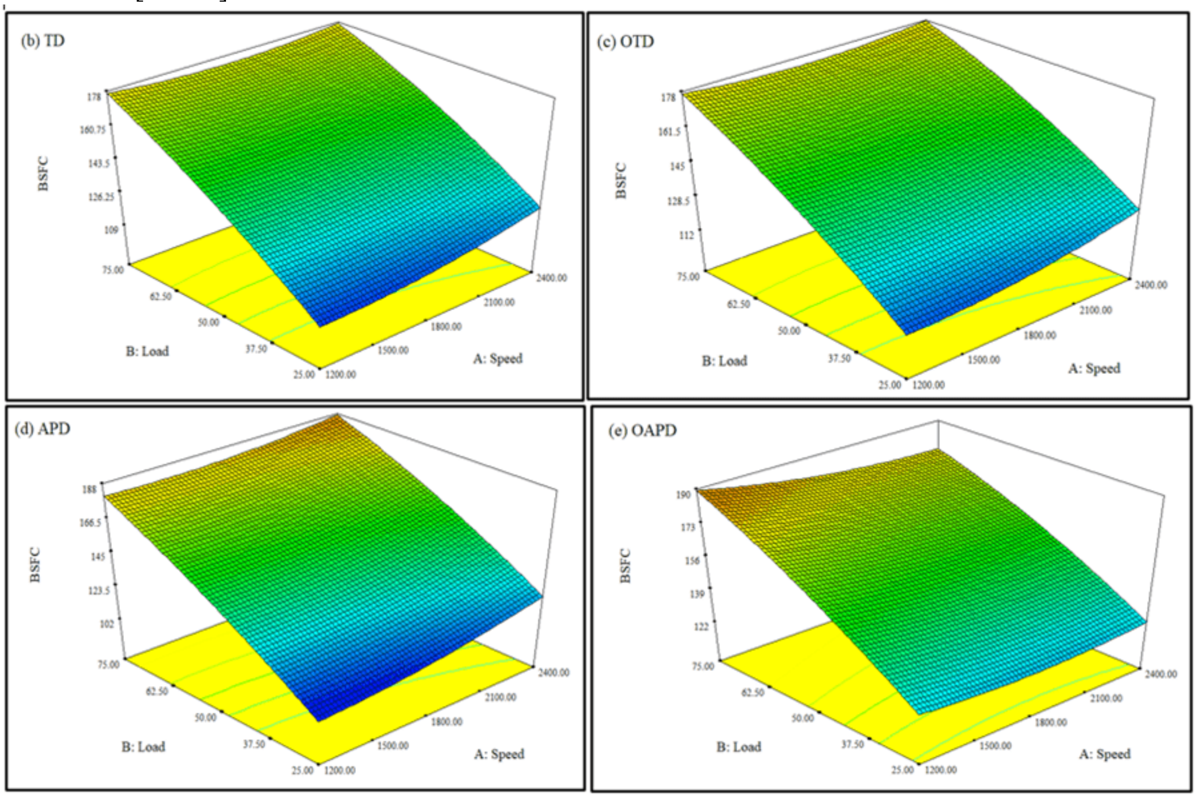

Figure 7: Continued

EGT analysis

Exhaust gas temperature is a critical parameter of the heat emitted by the tested fuel during combustion, as well as a factor in determining exhaust emission levels. **Table 5** shows the ANOVA data for the EGT of test fuels at various engine speeds and loads. The *F*-value for this model is 164.92, and the *p*-value is less than 0.0001, or less than 0.05, suggesting that the model is significant. The R^2 value is 98.3%. It also shows that the model has a difference between the Pred R-Squared (95.7%) and the Adj R-Squared (97.8%) of less than 0.02. The test fuel is a significant term in the ANOVA table, while the sum of squares indicates that the engine speed and loads have smaller effects. This tallies with the EGT equation. The relationship between EGT and engine speed (A), engine load (B), and fuels (C) is shown in **Eq. 4**, where C_1, C_2, C_3, C_4, and C_5 are D, TD, OTD, APD, and OAPD, respectively.

Table 5: Analysis of variance table for EGT

Source	Sum of Squares	df	Mean Square	*F*-Value	*p*-Value Prob > *F*	
Model	4.260E+005	17	25,061.30	164.92	<0.0001	significant
A-Speed	1.051E+005	1	1.051E+005	691.82	<0.0001	
B-Load	2.294E+005	1	2.294E+005	1,509.60	<0.0001	
C-Fuel	86,824.12	4	21706.03	142.84	<0.0001	
AB	1,936.12	1	1,936.12	12.74	0.0008	
AC	744.25	4	186.06	1.22	0.3133	
BC	682.59	4	170.65	1.12	0.3571	
A^2	1,169.85	1	1,169.85	7.70	0.0079	

Source	Sum of Squares	df	Mean Square	*F*-Value	*p*-Value Prob > *F*	
B^2	587.95	1	587.95	3.87	0.0551	
Residual	7,142.34	47	151.96			
Lack of Fit	7,069.71	27	261.84	72.11	<0.0001	significant
Pure Error	72.63	20	3.63			
Cor Total	4.332E+005	64				

R-Squared sum of squares 0.9835
Adj R-Squared sum of squares 0.9775
Pred R-Squared sum of squares 0.9566

$$EGT = 280.99 + 59.20A + 87.45B + 28.94C_1 + 36.58C_2 - 42.75C_3 + 23.37C_4 + 9.84AB + 2.70AC_1 - 3.40AC_2 + 1.69AC_3 + 6.64AC_4 + 1.70BC_1 + 4.84BC_2 + 0.32BC_3 + 2.22BC_4 + 9.20A^2 - 6.53B^2 \quad (4)$$

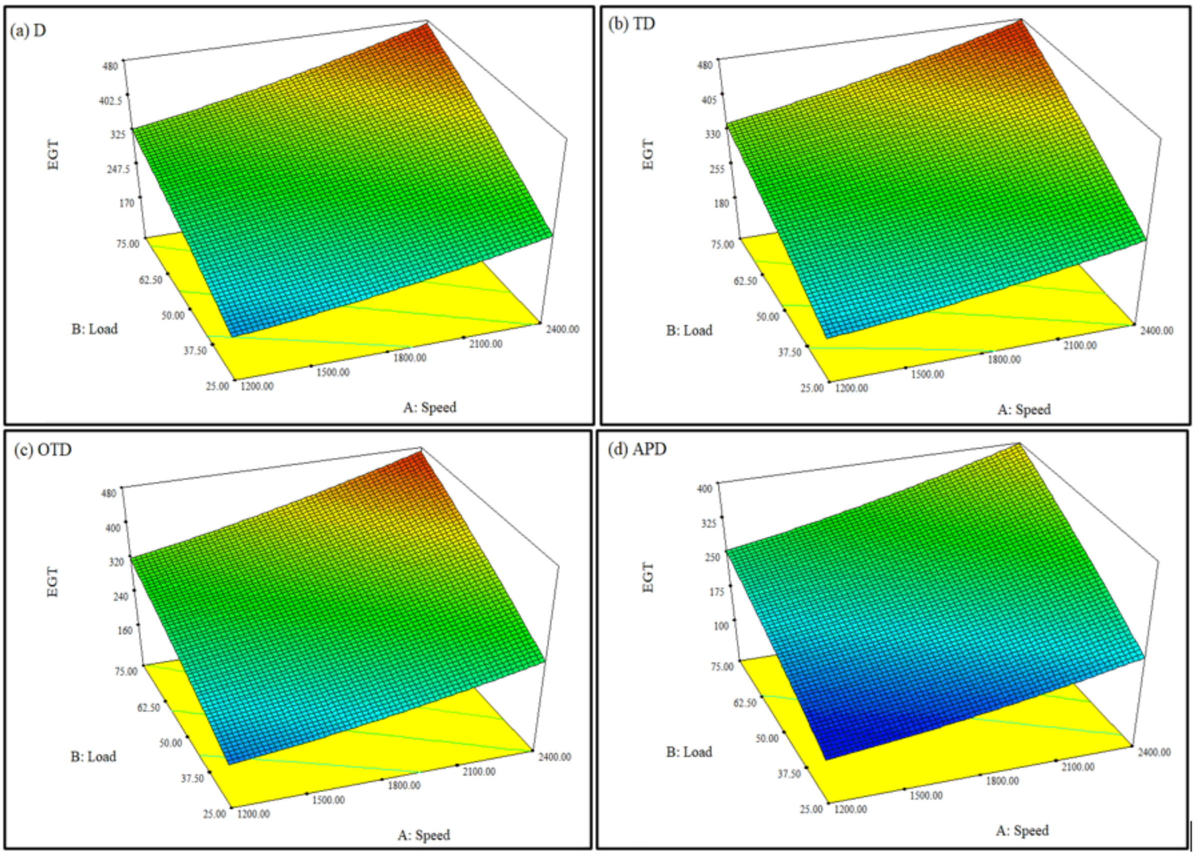

Figure 8: Response surface plots for EGT variation in test fuels of (a) D, (b) TD, (c) OTD, (d) APD, and (e) OAPD

The 3D response surface plots for the quadratic model of EGT of each fuel at various engine speeds and loads are shown in **Figure 8** (a–e). From **Figure 8** (a–e), it is notable that the EGT increased as the engine load increased for all fuel mixes, as presented by the contour maps. Additionally, as demonstrated in the 3D plots, the EGT also increased as the engine speed increased. Each test fuel's EGT minimum and maximum values varied from each other. For the baseline using D, **Figure 8** (a) indicates that for various engine speeds and loads, the EGT of D is in a range of 180–480 °C. **Figure 8** (b–e) illustrate the EGT separately for each test fuel with additives. The EGT of additive-diesel test fuels is between 100 °C and 480 °C. It is also notable that OAPD has the highest EGT (380 °C) among additive-diesel blends compared to diesel (480 °C), which is about 20.8% reduction. As evidenced by the variations in EGT, additives in the fuel blends and engine speeds have a significant effect on EGT. The slower combustion characteristics (late or extended combustion) of diesel fuel are a factor that affects EGT reduction with its additives. This could be due to the heat loss of the additive-diesel blends, as indicated by their higher BTE than diesel fuel. Turpentine oil's lower viscosity and low volatility result in improved atomisation and evaporation of the injected fuel, which reduces EGT. As a result, during the earliest phase of combustion, more fuel is prepared. Turpentine has a lower cetane number; hence, the amount of time available for fuel preparation during the ID period increases. Thus, more fuel is spent in the premixed combustion phase, whereas less fuel is utilised in the latter stage of combustion (diffusion combustion phase), resulting in lower EGTs. Furthermore, the decrease of EGT for additive-diesel blends can be explained by the higher combustion temperature of the fuels due to the existence of chemically bound O_2 content in turpentine-based oil. Moreover, the heat carried away by exhaust gases decreased, resulting in improved BTE of oxygenated additive-diesel blends when compared to diesel fuel [30]. Oher researchers observed similar outcomes by using other types of chemicals [31–34].

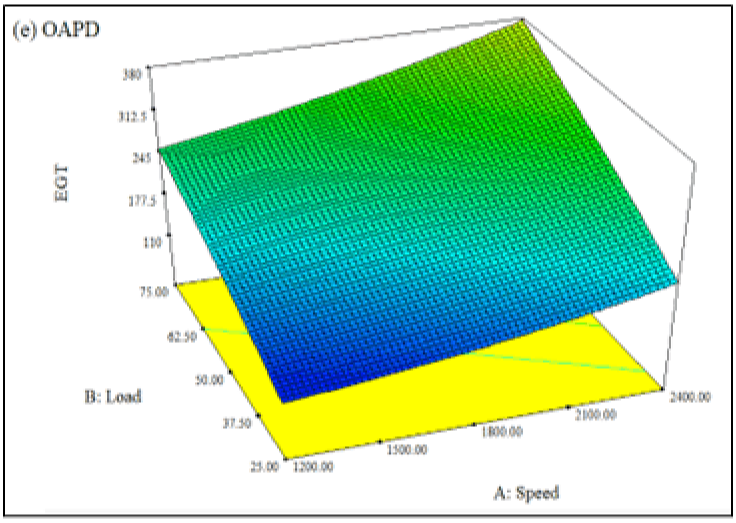

Figure 9: Continued

Conclusion

The experimental investigation and statistical analysis using Response Surface Methodology (RSM) confirmed that additive-diesel blends significantly affect engine performance, combustion behavior, and emission characteristics in a single-cylinder Yanmar TF120M diesel engine. Among the tested parameters, engine speed and load were found to have the most dominant influence, particularly on Brake Power (BP), Brake Thermal Efficiency (BTE), and Brake Specific Fuel Consumption (BSFC). The study revealed that BP improved by 3.1% to 8.1% when using additive blends such as TD, OTD, APD, and OAPD compared to baseline diesel (D). BTE reached its peak value of 35% with TD and APD blends, marking an improvement of up to 6.1%. Furthermore, BSFC was reduced significantly, with the lowest recorded value at 102 g/kWh for APD, representing a 12.8% reduction. Exhaust Gas Temperature (EGT) also decreased by up to 20.8% with OAPD, indicating more efficient combustion and lower heat losses. The developed quadratic models showed excellent agreement with experimental data, with R^2 values above 0.94 for most responses and adequate precision (AP) values well above the minimum threshold of 4. These findings demonstrate that incorporating oxygenated additives such as turpentine and alpha-pinene in diesel fuel can enhance engine efficiency and reduce harmful emissions, making them promising candidates for cleaner alternative fuels.

Acknowledgement

The Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia, fully supported this research.

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