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Development of an Optimum Alcohol-Gasoline Blend for Combustion in a Spark Ignition Engine

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ABSTRACT

The growing demand for clean and more efficient fuel options has led to an increased interest in alcohol-gasoline blends as an alternative to conventional gasoline for spark-ignition engines. This study focused on the development of an alcohol-gasoline blend with optimum physicochemical properties for spark ignition engines. Gasoline was obtained from a fuel station in Ogbomoso, Oyo State, while alcohol (methanol, ethanol and butanol) was procured from SAVIDEB Chemical Enterprises in Osogbo, Osun State. Fifteen experimental runs were developed from the mixture of methanol (5-20%), ethanol (5-20%), butanol (5-20%) and gasoline (70-85%) using the D-Optimal Mixture Design of Design Expert Software (13.0.1). Homogeneous blends of the mixture were obtained using a mechanical mixer. The blends were characterized by Lower Heating Value (LHV), density, Specific Gravity (SG), American Petroleum Institute Gravity (API G), Research Octane Number (RON), Motor Octane Number (MON), Antiknock Index (AKI), Vapour Pressure (VP), viscosity and Heat of Vaporisation (HOV), based on their respective ASTM standards. Model equations were obtained and their statistical properties were evaluated. Numerical optimisation was performed to obtain the Optimum Alcohol-Gasoline Blend (OAGB). The predicted responses of the OAGB were validated by experimentation and the percentage error was calculated for each response. The result showed that the physicochemical properties of blend-13 (5% methanol, 5% ethanol, 5% butanol and 85% gasoline) gave the experimental best. Numerical optimization of the process gave alcohol-gasoline blend (9.859% Methanol, 5% Ethanol, 5% Butanol and 80.141% Gasoline) with LHV, density, SG, API G, RON, MON, AKI, VP, viscosity and HOV of 40.55 MJ/kg, 742.91 kg/m^3, 0.749, 57.42, 101.20, 83.95, 92.58, 47.26 kPa, 0.630 mm^2/s and 439.50 kJ/kg as the OAGB. Validation of optimum alcohol-gasoline predicted physicochemical properties showed that research octane number gave the maximum % error of 1.847, while viscosity gave the minimum value of 0%. The study established that alcohol–gasoline blends have superior physicochemical properties and are therefore a reliable alternative source of renewable energy for spark ignition engines.

INTRODUCTION

The increasing global concern over environmental pollution and the finite availability of fossil fuels has necessitated the search for alternative fuels that are both sustainable and compatible with existing internal combustion engine technologies. Among the various alternatives, alcohols such as ethanol and methanol have emerged as promising candidates for use in spark-ignition (SI) engines, particularly in Direct Injection Spark Ignition (DISI) engines. Alcohol-gasoline blends have attracted significant attention due to their potential to improve combustion efficiency, reduce harmful emissions, and enhance engine performance when compared to traditional gasoline-only fuels (Ahmed *et al.,* 2021; Zhang *et al.,* 2022; Akbiyik *et al.,* 2023). Alcohols, particularly ethanol, methanol and butanol, are promising renewable alternatives to gasoline. These alcohols can

be blended with gasoline to reduce carbon emissions and improve combustion efficiency. Alcohol fuels offer several advantages for combustion in SI engines. One key advantage is their higher-octane rating, which allows for more aggressive combustion strategies and enables engines to operate at higher compression ratios without knocking. Alcohols also have a higher latent heat of vaporization, which leads to better charge cooling in the cylinder, enhancing volumetric efficiency and reducing the risk of pre-ignition. Furthermore, alcohol fuels are oxygenated, meaning they contain oxygen in their molecular structure, which promotes cleaner combustion and reduces emissions of carbon monoxide (CO) and unburnt hydrocarbons (HC) (Zhou *et al.,* 2016; Costa *et al.,* 2021; Iliev *et al.,* 2021).

In particular, Direct Injection Spark Ignition (DISI) engines have been shown to respond well to alcohol-gasoline blends due to their ability to finely control fuel injection timing and quantity. This allows for better atomization and mixing of the fuel-air charge, leading to more complete combustion. The use of alcohol-gasoline blends in DISI engines has been linked to improvements in brake thermal efficiency**.** The use of alcohol in internal combustion engines is not without challenges. Lower energy density requires the engine to consume more fuel to generate the same power output as gasoline. Additionally, high concentrations of alcohols may cause corrosion and compatibility issues with certain engine materials, particularly in the fuel injection and storage systems. These issues must also be addressed to optimize the blend ratio. The key problem lies in finding the right balance between alcohol and gasoline that maximizes the benefits, such as improved combustion efficiency and reduced emissions, while minimizing the drawbacks, such as higher fuel consumption and engine wear. Therefore, there is a pressing need to develop an optimum alcohol-gasoline blend that can be efficiently combusted in DISI engines without compromising performance, fuel economy, or engine durability (Heywood, 2018; Jiahong *et al.,* 2022). The objective of this research is to identify the optimum alcohol-gasoline blend ratio for combustion in DISI engines. By evaluating various physicochemical and fuel properties, this study aims to develop a blend that balances the benefits of alcohol fuels with the practical limitations of their use in conventional engines.

METHODOLOGY

Alcohol-gasoline blend ratios were determined using the D-optimal mixture design of the Design Expert Software (13.0.1). Methanol, ethanol, butanol and gasoline were measured with different measuring cylinders and poured into a beaker. The mixture was then agitated vigorously to make a homogeneous blend. The mixture components and the levels that were used are shown in Table 1. Fuel characterization was done on the alcohol-gasoline blends produced with a specific focus on the ASTM standard test for liquid fuels. The blends were characterized for the following: Lower Heating Value (LHV), density, Specific Gravity (SG), American Petroleum Institute Gravity (API G), Research Octane Number (RON), Motor Octane Number (MON), Antiknock Index (AKI), Vapour Pressure (VP) and viscosity and Heat of Vaporisation (HOV).

Lower Heating Value

The heating value was determined according to ASTM D240. 20 ml of alcohol-gasoline blends was burned in a bomb calorimeter connected to a galvanometer. The burned fuel in the calorimeter produced hot gases that deflected the galvanometer. The hot gases were replaced by pure oxygen, and the effect on a galvanometer was recorded. The procedure was repeated for pure and dry benzoic acid, and the lower heating value of the blend was computed with Equation 1 used by Bhandare, and Naik, (2015).

$$\text{Lower Heating Value (LHV)} = \frac{(A-B)\times C}{D} \quad 1$$

Where: A is the galvanometer deflection with alcohol-gasoline blends, B is the galvanometer deflection with pure oxygen, C is the calibration constant given by equation 2, and D is the mass of alcohol-gasoline blend used.

$$C = \frac{6.32M}{E-B} \quad (2)$$

Where: E is the galvanometer deflection with benzoic acid, and M is the mass of benzoic acid.

Density: The density of the alcohol-gasoline blends was determined according to the method described in ASTM D4052.

Specific Gravity (SG)

SG of alcohol-gasoline blends was determined according to the ASTM D4052 standard. The specific gravity of each blend was obtained by weighing an empty pycnometer on a sensitive weighing balance. 25 ml of the alcohol-gasoline blend at 30 ºC was poured into the pycnometer and weighed. Distilled water (25 ml) was poured into the pycnometer and weighed after the blend had been poured out and the pycnometer had been adequately cleaned. SG of each blend was obtained by (Bhandare and Naik 2015) in Equation 3.

$$SG = \frac{W2-W1}{Ww-W1} \quad (3)$$

Where W_1 is the weight of an empty pycnometer (g), W_2 is the weight of a pycnometer and alcohol-gasoline blends (g) and W_w is the weight of a pycnometer and distilled water (g).

American Petroleum Institute Gravity (API G)

The API G for the alcohol-gasoline blends was determined using Equation 4

$$\text{API G} = \frac{141.5}{SG} - 131.5 \quad (4)$$

Octane index

The octane index for alcohol-gasoline blends was determined using ASTM D2700 to obtain motor octane numbers and by using ASTM D2699 to obtain research octane numbers. The Octane number was determined by comparing the characteristics of gasoline to isooctane (2, 2, 4-trimethylpentane), and heptane is assigned an octane number of 100. It is a highly branched compound that burns smoothly with a little knock. Two octane numbers are routinely used to simulate engine performance: The Research Octane Number (RON) simulates gasoline performance under low severity (at 600 rpm and 49°C air temperature), whereas the Motor Octane Number (MON) reflects more severe conditions (at 900 rpm and 149°C air temperature). Therefore, RON in conjunction with MON defines the antiknock index (AKI) of SI engine fuels given by Equation 5.

$$\text{Antiknock index} = \frac{(RON+MON)}{2} \quad (5)$$

Vapour pressure

The vapour pressure of each alcohol-gasoline blend was determined using ASTM D5191. 10 ml of chilled, air-saturated alcohol-gasoline blend sample was introduced into a thermostatically controlled, evacuated test chamber. After introduction into the test chamber, the alcohol-gasoline blend was allowed to reach thermal equilibrium at the test temperature of 37.8 °C. The resulting rise in pressure in the chamber was measured using a pressure transducer sensor and indicator.

Viscosity

The kinematic viscosity of the alcohol-gasoline blends was determined according to ASTM D445 standard, using the Cannon-Fenske Capillary Viscometer Tube. The alcohol-gasoline blend of 50 mL was poured into the viscometer tube, and the tube was suspended in a water bath mounted on a hot plate to raise the temperature of the blend to 40 ^{o}C for 30 minutes. The time taken for 50 mL of this blend to flow under gravity through the capillary of the calibrated viscometer at 40 ^{o}C was recorded. The kinematic viscosity in mm^2/s is equal to the product of the time and a calibration constant (Bhandare and Naik, 2015). It is expressed as Equation 6:

$$V = Kt \quad (6)$$

Where K is the calibration constant of the viscometer tube in $m^2//s^2m$ t is time in s

Heat of Vapourisation (HOV)

The HOV for alcohol-gasoline blends was determined using ASTM D2890-92. Heat capacities obtained by this method are those at atmospheric pressure.

Table 1: Alcohol-gasoline Components and Levels

Mixture Components		Level	
	Unit	Low (-1)	High (+1)
Methanol	%	5	20
Ethanol	%	5	20
Butanol	%	5	20
Gasoline%	%	70	85

D-optimal mixture design in Design Expert (13.0.1) was used to determine the alcohol-gasoline optimum blend to obtain the blend with the best fuel properties. D-optimal mixture design with four factors and ten responses was used to construct mathematical models for the blend ratio optimization process. According to the D-optimal mixture design approach, the influence of these components on physicochemical properties was determined and an optimum combination was evaluated. For optimization, depending on the effect of each factor, the combination of factors that led to the best responses was evaluated. The adequacy of the model was determined by assessing the *p*-value of the lack of fit, coefficient of determination (R^2), and ANOVA F-value. The predicted responses were validated by experimentation and the percentage Error (% Error) was calculated for each response using Equation 7 given as

$$\% \text{ Error} = \frac{P-A}{A} \text{ x } 100 \quad (7)$$

Where: P is the predicted value and A is the actual (experimental) value.

D-optimal mixture design was used in blend formulation to determine the effect of blend ratio on the physicochemical properties of alcohol-gasoline blends. D-optimal design was constructed to minimize the overall variance of the predicted regression coefficient by maximizing the value of the determinant of the information matrix. The statistical parameters used in evaluating and selecting the best-fitted model are the coefficient of determination (R^2), adjusted coefficient of determination (adjusted R^2), predicted coefficient of determination (predicted R^2), and ANOVA data.

RESULTS AND DISCUSSION

The result of the characterization of alcohol-gasoline blends is shown in Table 3. The design of the experiment was done using D-optimal mixture design in Design Expert 13.0.1. It has 15 runs, 4 components and 10 responses. The responses are the physicochemical properties of the blends obtained through experiments. The desired physicochemical properties of the blends are the highest LHV, lowest density, lowest SG, highest API G, highest RON, highest MON, highest AKI, highest VP, lowest viscosity and lowest HOV. Each blend comprises methanol, ethanol, butanol and gasoline at different ratios. It can be seen from Table 2 that Blend-13 (5% methanol, 5% ethanol, 5% butanol and 85% gasoline) has the highest LHV value of 40.55 MJ/kg while Blend-2 (20% methanol, 5% ethanol, 5% butanol and 70% gasoline) has the lowest LHV of 37.10 MJ/kg. The result showed that the higher the gasoline content of the blend, the higher the LHV. This is because pure gasoline is more energy-dense than alcohol fuels. This finding is in agreement with the work of Mateus *et al.* (2023). This implies that Blend-13 is the most desirable in terms of LHV. The highest density of 757.45 kg/m^3 was obtained from Blend-14 (5% methanol, 5% ethanol, 20% butanol and 70% gasoline) and the lowest density of 742.91 kg/m^3 was obtained from Blend-13, hence, Blend-13 is the most desirable in terms of density.

This result showed that the lower the gasoline content of the blend, the higher the density. The highest SG value of 0.760 was obtained from Blend-14, while the lowest SG value of 0.749 was obtained from Blend-13. This showed that the lower the gasoline content of the blend, the higher the SG value and Blend-13 is the most desirable in terms of SG. Blend-13 gave the highest API G value of 57.42 while Blend-14 gave the lowest API G value of 54.68. This indicates that the higher the gasoline content of the blend, the higher the API G value. This result showed that Blend-13 is the most desirable while Blend-14 is the least desirable in terms of API G. This result is in line with the result obtained by Elshenawy *et al.* (2023) with the same trend. Blend 2 gave the highest RON of 106.45, the highest MON of 87.40 and the highest AKI of 96.93, while Blend-14 gave the lowest RON of 100.90, the lowest MON of 83.35, and the lowest AKI of 92.13. These results indicate that the lower the gasoline content and the higher the methanol content of the blend, the higher the RON, MON and AKI. This showed that Blend 2 is the most desirable in terms of RON, MON and AKI, while Blend-14 is the least desirable. This finding is in agreement with the work of Xuan *et al*. (2022) and Veza *et al.* (2023). The highest VP value of 47.26 kPa was obtained from Blend-13, while the lowest value of 39.55 kPa was obtained from Blend-14. This showed that the higher the gasoline content of the blend, the higher the VP and the higher the butanol content of the blend the lower the VP. Blend-13 is the most desirable while Blend-14 is the least desirable. It can be seen from Table 4.1 that the highest viscosity value of 0.900 mm^2/s was obtained from Blend-14, while the lowest value, 0.630 mm^2/s was obtained from Blend-13. Hence, Blend-13 is the most desirable while Blend-14 is the least desirable in terms of viscosity. This indicates that the higher the gasoline content of the blend, the lower the viscosity, whereas the lower the gasoline content and the higher the butanol content of the blend the higher the viscosity. This result is in agreement with the result obtained by Mateus *et al*. (2023).

Table 2 shows that Blend 2 gave the highest HOV value of 549.00 kJ/kg while Blend 13 gave the lowest value of 439.50 kJ/kg; hence, Blend 13 is the most desirable and Blend 2 is the least desirable in terms of HOV. This indicates that the higher the methanol content of the blend and the lower the gasoline content, the higher the HOV value. The results showed that Blend-13 is the most desirable in seven out of ten physicochemical properties

considered, while Blend 2 is the most desirable blend in three and the least desirable blend in two properties. Blend-14 is the least desirable in eight out of ten properties considered.

Predictive Models for Alcohol-gasoline Blends Physicochemical Properties

Models to predict the physicochemical properties of Alcohol-gasoline blends were developed using a D-optimal mixture design in Design Expert 13.0.1. The models (Equations 8-17), eight linear and two quadratic, were developed in terms of coded factors for all ten physicochemical properties considered in this study. The quality of the models developed was evaluated based on statistical methods.

$$\text{LHV} = 37.11A + 38.15B + 39.05C + 40.55D \quad (8)$$

$$\text{Density} = 753.82A + 753.22B + 757.45C + 743.08D - 0.4937AB - 0.4368AC + 6.71AD - 0.4368BC + 6.71BD + 4.93CD \quad (9)$$

$$\text{SG} = 0.7562A + 0.7559B + 0.7596C + 0.7488D \quad (10)$$

$$\text{APIG} = 55.62A + 55.69B + 54.77C + 57.47D \quad (11)$$

$$\text{RON} = 106.45A + 105.85B + 100.90C + 101.20D \quad (12)$$

$$\text{MON} = 87.40A + 86.95B + 83.35C + 83.95D \quad (13)$$

$$\text{AKI} = 96.93A + 96.40B + 92.13C + 92.58D \quad (14)$$

$$\text{VP} = 41.69A + 40.35B + 39.55C + 47.26D \quad (15)$$

$$\text{Viscosity} = 0.6451\ A + 0.7351\ B + 0.9002\ C + 0.6302D \quad (16)$$

$$\text{HOV} = 548.90A + 510.06B + 471.06C + 439.56D - 6.22AB - 6.22AC - 6.22AD + 0.0972BC + 0.0972BD + 0.0972CD \quad (17)$$

Where A is methanol, B is ethanol, C is butanol and D is gasoline

Model Summary Statistics

The model summary statistics presented in Table 3 indicate that a linear model is suggested for LHV since it has the highest R^2 value of 1.0000. The predicted R^2 value of 0.9999 is in agreement with the adjusted R^2 value of 0.9999. A high Adeq Precision value of 982.698, which is greater than 4, indicates that the model is significant and the signal is adequate. The low value of standard deviation and Coefficient of Variation (CV) was an indication that the predicted value of LHV would be accurate and closer to the actual experimental value (Mohd *et al.,* 2011). A quadratic model is suggested for density since it has the highest R^2 value of 0.9963. The predicted R^2 value of 0.9897 is in reasonable agreement with the adjusted R^2 value of 0.9021 since the difference is less than 0.2. A high value of Adeq Precision of 49.986 (greater than 4) indicates that the signal is adequate and the model can be used to navigate the design space. The low values of C.V (0.0468) and standard deviation (0.3520) indicate that the model can be used to predict the value of alcohol-gasoline blends accurately (Montgomery, 2005; Onawumi *et al.,* 2019).

Table 3 shows that a linear model is suggested for SG and API G because it has the highest R^2 values of 0.9606 and 0.9615, respectively. The predicted R^2 value for SG and API G were 0.9350 and 0.9366, respectively, which were in reasonable agreement and closer to their corresponding adjusted R^2 value of 0.9498 and 0.9509, respectively. The high Adeq Precision values of 32.9327 and 33.3028 (greater than 4) for SG and API G indicate

that the models developed can be used to navigate the design space. The low values of C.V. and standard deviation obtained for SG and API G indicate a high precision and reliability of the predicted value.

Linear models are suggested for RON, MON, AKI, VP and Viscosity since it has the highest R^2 value of 1.0000 each for the five properties. The predicted R^2 value of 1.0000 for each of these properties is in agreement with the adjusted R^2 of 1.0000 for these five properties. The very high Adeq Precision values of 3835.2004, 3217.9895, 2973.490, 5448.8735 and 1694.2366 for RON, MON, AKI, VP and Viscosity, respectively, indicate that the signal is adequate and the models are significant, hence, they can be used to navigate the design space. The very low values of C.V of 0.0027, 0.0029, 0.0033, 0.0065 and 0.0424 coupled with very low values of the standard deviation of 0,0028, 0.0024, 0.0031, 0.0027 and 0.0003 for RON, MON, AKI, VP and Viscosity respectively mean that the developed models can be used for accurate and reliable prediction of the value of each of these properties (Mohd *et al.,* 2011).

Table 3 shows that a quadratic model is suggested for HOV since it has the highest R^2 value of 1.0000. The predicted R^2 value of 0.9991 is in reasonable agreement with the adjusted R^2 value of 0.9999 (the difference is less than 0.2). Adeq Precision, which measures the signal-to-noise ratio, is 446.7191, which indicates that the signal is adequate. The low value of C.V. and standard deviation of 0.0610 and 0.2998, respectively, indicate that the model can be used for accurate prediction.

Analysis of Variance (ANOVA) of the Alcohol-gasoline Blend Properties

The significance and adequacy of the developed models were justified through ANOVA. The high model F-values of 80971.27, 151.00, 89.35 and 91.46 obtained for LHV, density, SG, and API G, respectively, as shown in Table 4, imply the models are significant and there is only a 0.01% chance that F-values this large could occur due to noise. P-values less than 0.0500 imply model terms are significant and values greater than 0.1000 imply that the model terms are not significant. The P-value of < 0.0001 obtained for each of these properties indicates that the developed model terms are significant. The model F-values obtained for RON, MON and AKI are 1.949E+06, 1.247E+06 and 1.124E+06, respectively, indicating that the models are significant and there is a 0.01% chance that F-values this large could occur due to noise. P-values < 0.0001 obtained for these properties imply that the models are significant since it is less than 0.05.

Table 4 showed that the model F-values of 2.822E+06, 2.826E+06 and 14341.08 were obtained for VP, viscosity and HOV, respectively. This indicates that the models are significant and there is a 0.01% chance that F-values of this magnitude could occur due to noise. P-values of <0.0001 obtained for these properties imply that the model terms are significant.

Numerical Optimization of Alcohol-gasoline Blends

Numerical optimization of alcohol-gasoline blends was conducted with Design Expert software 13.0.1. All the selected factors (methanol, ethanol, butanol and gasoline were set to 'is in range' while the physicochemical properties of the blend were set to either maximize or minimize as appropriate according to its optimal value (Table 5). Numerical optimization of the process gave three solutions and the optimum blend selected was based on the highest desirability shown in Figure 1. In this study, the highest desirability was 0.622 while the optimum blend ratio suggested was 9.859% methanol, 5.0% ethanol, 5% butanol and 80.141% gasoline (Table 6).

Table 2: Physicochemical Properties of Alcohol-Gasoline Blends

Run	Component (%)				Response									
	A: Methanol	B: Ethanol	C: Butanol	D: Gasoline	LHV MJ/kg	Density kg/m^3	SG	API G	RON	MON	AKI	VP kPa	viscosity mm^2/s	HOV kJ/kg
1	8.75	8.75	8.75	73.75	38.71	752.71	0.755	55.92	103.6	85.41	94.51	42.21	0.728	491.00
2	20	5	5	70	37.1	753.85	0.756	55.67	106.45	87.4	96.93	41.69	0.645	549.00
3	5	5	12.5	77.5	39.8	751.42	0.754	56.17	101.05	83.65	92.35	43.41	0.765	455.25
4	12.5	5	12.5	70	38.1	755.65	0.758	55.18	103.68	85.38	94.53	40.62	0.773	508.50
5	5	12.5	12.5	70	38.6	755.35	0.759	54.93	103.38	85.15	94.27	39.95	0.818	490.50
6	6.875	14.375	6.875	71.875	38.43	752.98	0.755	55.92	104.73	86.18	95.46	41.28	0.731	500.81
7	6.875	6.875	14.375	71.875	38.88	755.10	0.756	55.67	102.25	84.38	93.32	40.88	0.814	481.31
8	6.875	6.875	6.875	79.375	39.63	749.51	0.752	56.66	102.40	84.68	93.54	44.74	0.679	465.56
9	12.5	5	5	77.5	38.83	750.08	0.753	56.42	103.83	85.68	94.76	44.48	0.638	492.75
10	14.375	6.875	6.875	71.875	37.91	753.28	0.756	55.67	105.03	86.41	95.72	41.95	0.686	518.81
11	5	20	5	70	38.15	753.25	0.756	55.67	105.85	86.95	96.40	40.35	0.735	510.00
12	12.5	12.5	5	70	37.63	753.55	0.756	55.67	106.15	87.18	96.67	41.02	0.690	528.00
13	5	5	5	85	40.55	742.91	0.749	57.42	101.20	83.95	92.58	47.26	0.630	439.50
14	5	5	20	70	39.05	757.45	0.760	54.68	100.90	83.35	92.13	39.55	0.900	471.00
15	5	12.5	5	77.5	39.35	749.78	0.752	56.66	103.53	85.45	94.49	43.80	0.683	474.75

Table 3: Model Summary Statistic for the Responses

Properties	LHV	Density	SG	APIG	RON	MON	AKI	VP	VISCOSITY	HOV
Model	Linear	Quadratic	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Quadratic
R^2	1.0000	0.9963	0.9606	0.9615	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Adj-R^2	0.9999	0.9897	0.9498	0.9509	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
Pred. R^2	0.9999	0.9021	0.9350	0.9366	1.0000	1.0000	1.0000	1.0000	1.0000	0.9991
Adeq Precision	982.6980	49.9860	32.9327	33.3028	3835.2004	3217.9895	2973.4940	5448.8735	1694.2366	446.7191
PRESS	0.0010	16.54	0.0007	0.4451	0.0002	0.0001	0.0002	0.0002	0.00001	10.47
CV	0.0175	0.0468	0.0845	0.2606	0.0027	0.0029	0.0033	0.0065	0.0424	0.0610
Std. Dev	0.0068	0.3520	0.0006	0.1568	0.0028	0.0024	0.0031	0.0027	0.0003	0.2998

Table 4: Analysis of Variance (ANOVA) for the Responses

Properties	LHV	Density	SG	APIG	RON	MON	AKI	VP	VISCOSITY	HOV
Model	Linear	Quadratic	Linear	Linear	Linear	Linear	Linear	Linear	Linear	Quadratic
Sum of Squares	11.16	168.36	0.0001	6.75	45.94	22.27	32.99	63.58	0.0808	11599.02
DF	3	9	3	3	3	3	3	3	3	9
Mean Square	3.72	18.71	0.000	2.25	15.31	7.42	11.00	21.19	0.0269	1288.78
F-value	80971.27	151.00	89.35	91.46	1.949×10^{6}	1.247×10^{6}	1.124×10^{6}	2.822×10^{6}	2.826×10^{5}	14341.08
P-value	<0.0010	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 5: Optimization constraints for alcohol-gasoline blends

Name	**Goal**	**Lower Limit**	**Upper Limit**
A: METHANOL	is in range	5	20
B: ETHANOL	is in range	5	20
C: BUTANOL	is in range	5	20
D: GASOLINE	is in range	70	85
LHV	Maximize	37.1	40.55
Density	Minimize	742.91	757.45
SG	Minimize	0.749	0.76
API G	Maximize	54.68	57.42
RON	Maximize	100.9	106.45
MON	Maximize	83.35	87.4
AKI	Maximize	92.13	96.93
VP	Maximize	39.55	47.26
Viscosity	Minimize	0.63	0.9
HOV	Minimize	439.5	549

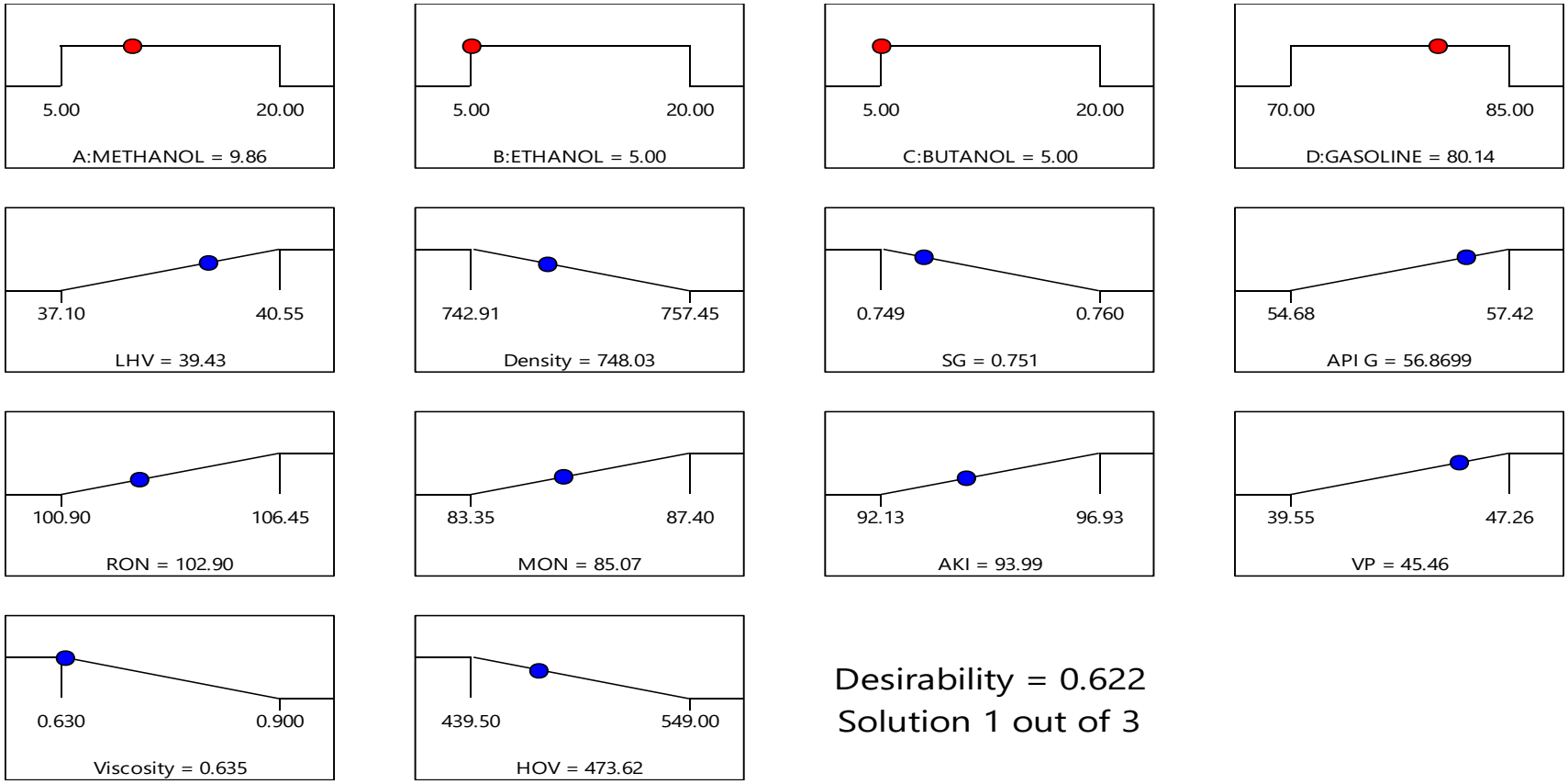

Figure 1: Numerical optimisation result desirability for optimum alcohol-gasoline blends

Table 6: Numerical optimization result

Number	Fuel				Properties									
	Methanol	**Ethanol**	**Butanol**	**Gasoline**	**LHV**	**Density**	**SG**	**API G**	**RON**	**MON**	**AKI**	**VP**	**Viscosity**	**HOV**
1	9.859	5.000	5.000	80.141	39.434	748.030	0.751	56.870	102.903	85.069	93.988	45.457	0.635	73.619
2	5.000	10.174	5.000	79.826	39.720	748.096	0.751	56.855	102.806	84.985	93.897	44.877	0.666	463.900
3	6.734	18.266	5.000	70.000	38.028	753.238	0.756	55.681	105.922	87.002	96.465	40.503	0.725	513.913

Table 7: Validation result of the optimum blend

S/N	Parameters	Predicted	Experimental	% Error
1	Latent Heat of vaporization (LHV)	39.434	39.75	0.795
2	Density	748.030	743.75	0.575
3	Specific Gravity (SG)	0.751	0.748	0.401
4	API Gravity (API G)	56.870	57.90	1.779
5	Research Octane Number (RON)	102.903	103.95	1.847
6	Motor Octane Index (MON)	85.069	85.91	0.979
7	Anti Knock Index (AKI)	93.988	94.50	0.542
8	Vapour Pressure (VP)	45.457	46.15	1.502
9	Viscosity	0.635	0.635	0
10	Heat of Vaporization (HOV)	473.619	470.62	0.637

The validation result of the optimum blend (Table 7) shows the experimental value, the predicted value and the % error. The maximum % error of 1.847 was obtained for RON while the minimum value of 0% was obtained for viscosity. This implies a high precision and reliability of the optimization process.

CONCLUSION

Based on the findings from this study, alcohol-gasoline blends have superior combustion and performance characteristics compared with pure gasoline. The following conclusions were drawn:

i. D-optimal mixture design in Design Expert 13.0.1. was used to develop alcohol-gasoline blends and the result of characterization showed that Blend-13 (5% methanol, 5% ethanol, 5% butanol and 85% gasoline) has the best fuel properties.

ii. Models to predict the physicochemical properties of alcohol-gasoline blends were developed. The model summary statistics and ANOVA showed that all the models and model terms are significant; therefore, the model can be used to navigate the design space.

iii. The optimum blend selected (9.859% methanol, 5.0% ethanol, 5% butanol and 80.141% gasoline) was based on the highest desirability.

iv. The result of validation showed that the maximum % error of 1.847 was obtained for RON, while the minimum value of 0% was obtained for viscosity.

v. This study contributes to the growing body of research on renewable fuels and their role in achieving sustainable energy solutions in transportation. By identifying optimum alcohol-gasoline blends, this research supports the transition to cleaner, more efficient engines capable of meeting increasingly stringent environmental standards.

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