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Blending Optimization on The Fuel Characterization of Sunflower Oil - Pentanol Binary Biofuel Blend

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Abstract **—Straight vegetable oil (SVO) such as Pure Sunflower Oil (PSO) is a possible alternative biofuel to petroleum diesel fuel because of its physical qualities identical to fossil fuel. However, the higher viscosity and density of PSO limits its direct use in the combustion engines. This work presents an experimental investigation to determine and optimize the key properties of the Sunflower oil-Pentanol blend, which is potential to be used to replace the existing fossil fuel. This study proposes a binary biofuel blend of pure sunflower oil (PSO) with higher alcohol pentanol (PEN). Pentanol has lower kinematic viscosity, density, and calorific value as compared to PSO. In this study, Mixture design method is used to formulate, optimize, and predict the key properties of this binary biofuel blend. Based on mixture design analysis, a total of 8 blend ratios which varies from 100PSO and 100PEN were proposed. The developed equation and experimental data for the density, kinematic viscosity, and calorific value** equations **all yielded good results. The predicted values were within 0.012 to 7.14 % of the experimental results, showing the accuracy of the developed equations. The blend ratio of 30PSO70PEN was determined to be the most optimal, with response values of density, kinematic viscosity, and calorific value of 875.966 kg/m³, 5.99 mm²/s, and 36068.7 kJ/kg, respectively. All these responses meet the ASTM D6751 requirements for biodiesel and are suitable for use in a Compression Ignition engine.**

Keywords—Pure Sunflower Oil, Pentanol, Mixture Design Expert, Fuel characterization.

I. INTRODUCTION

Recently, many studies have been done on the use of straight vegetable oil (SVO) as engine fuel as an alternative for petroleum diesel due to the depleting fossil fuel [1]. SVO are generally produced by mechanically extracting oil from a biomass feedstock that contains oil. [1-2]. SVO have fuel characteristics comparable to petroleum diesel, making them ideal for use as fuel in diesel engines [2]. This is because SVO are renewable, readily available from a range of sources, have low sulphur levels near zero, and hence have a less environmental impact than diesel which has drawn the attention of many researchers worldwide [3]. The presence of sulphur minimizes the amount of corrosion in the engine crankcase produced by sulphuric acid development and reduces sulphur dioxide emissions into the atmosphere, which can create acid rain [4].

Nowadays, the production of vegetable oil is growing day by day around the world. This indicates that oil stocks today are more plentiful and readily available and processed. Each country produces different oil stocks according to the changing seasons of a country. Among the countries that produce the most oil in Europe, the country produces a large stock of rapeseed oil and sunflower oil [5]. Vegetable oils are derived from plants, generally from the seeds, and common vegetable oils include rapeseed oil, sunflower oil, and palm oil [6]. Generally, vegetable oil can be divided into two types which are edible and non-edible oils [7]. Edible oils include palm oil, sunflower oil, soybean oil, and rapeseed oil, while non-edible oils include jatropha, castor, and Karanja oils. Palm oil has the most excellent oil yield among edible oils, followed by sunflower oil. In contrast,

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jatropha and Karanja (Pongamia pinnata) have the highest oil yield for non-edible oil.

Although SVO have the potential to be utilised as engine fuel, there are some drawbacks. One of the most significant issues is the high oil viscosity, which causes carbon deposits on the injectors, poor fuel atomization, and incomplete combustion [8-9]. According to a previous study, the difficulties seen in long-term engine testing may be characterized as follows: coking on injectors increased carbon deposits, oil ring sticking, and thickening and gelling of the engine lubricating oil [10]. Vegetable oils may be used as fuel for diesel engines, although their viscosities are significantly greater than standard diesel fuel, requiring engine modifications [11]. Researchers conducted an experiment using pure sunflower oil to evaluate its performance and emissions properties at various engine loads and speeds. They discovered that compared to diesel fuel, Brake Thermal Efficiency (BTE), Brake Power (BP), and torque were lower, while Brake Specific Fuel Consumption (BSFC) was greater [12]. Oxides of Nitrogen (NO_X) emissions were considerably decreased in the test range, while Carbon Monoxide (CO) and Carbon Dioxide (CO_2) emissions increased [13, 14]. Direct use of vegetable oil oxidative and thermal polymerization results in a deposition on the injectors, producing a film that traps fuel and interferes with combustion [15]. In the long run, vegetable oils are susceptible to gumming, injector coking, and ring sticking [16]. As a result, using pure vegetable oils in diesel engines is not recommended.

In the previous studies, many researchers often used alcohol for blending with vegetable oil. Most of them used short-chain alcohols like ethanol and methanol as components of blends to be used in diesel engines because they have certain benefits over diesel [17-19]. On the other hand, researchers have also recently explored the mixes of longer-chain alcohols with SVO like butanol and pentanol as components of blends, owing to their similar characteristics to diesel fuel [19-20]. Previous and ongoing studies on the use of pentanol in Internal Combustion (IC) engines are effective due to their ability to reduce reliance on diesel fuel by increasing renewable fuels. Pentanol is an excellent corrosion inhibitor that does not affect fuel lines. Pentanol blends usually have lower viscosities, higher oxygen content, and better ignition quality, all of which help with atomization and combustion. Pentanol blends are more stable and have no phase separation [21]. In another studies, Rapeseed oil (RSO) characteristics mixed with higher alcohol concentrations (butanol and pentanol). They discovered that as the proportion of alcohol increased, the viscosity, density, flash point, Calorific Value (CV), and cetane number of the blends reduced [22]. The viscosity decreases substantially as the temperature increases [23]. The delay duration of the blend increases as pentanol content increases, increasing the pre-mixed CV and allowing for higher peak cylinder pressure. The dominance of pentanol's inferior CV results in low combustion temperatures at low and medium loads. The dominance of premixed combustion, on the other hand, leads to high combustion temperatures at full load conditions [24].

Therefore, the method of blending vegetable oil specifically Sunflower oil with higher alcohol was adopted to solve this issue. This binary blend is expected to overcome the above issues while also providing suitable fuel properties for internal combustion engines. This project aims to determine sunflower oil and pentanol blend properties by experimenting with formulating and analysing the kinematic viscosity, density, and calorific value of a certain amount of blend. The data obtained by the experiment is recorded. It is then transferred to the simulation of the mixture using Design-Expert software. This software allows to run a simulation and helps to predict whether the blend of sunflower oil-pentanol is suitable or not suitable to be used to replace fossil fuels. The accuracy of software prediction will then be tested, and the results will be optimized and validated. Finally, an analysis of the data will be performed to discuss and draw conclusions based on the results

II. METHODOLOGY

A. Material

Sunflower Oil (PSO) test fuel was bought from a local supermarket for the binary biofuel formulation. The oil is light yellowish, clear, and has a sweetish taste but no odour. The fuel production using SVO is simpler as that diesel fuel has a cetane number similar to SVO, and the heating value is nearly 90% compared to diesel fuel. Meanwhile, Pentanol was obtained from a chemical laboratory since it required safety precautions and was not intended for public use. This substance is colourless and has a high solubility in stable blends with no phase separation. Pentanol blends have more oxygen content and better ignition quality, which improves the engine performance compared to lower alcohol, which is poor in the lubricating properties that lead to the increase of engine wear.

B. Design Expert Software

In this project, mixture design has been constructed and analysed using the latest commercially available Design-Expert software version 12. Design-Expert software provides innovative statistical tools for response surface methods as well as mixture optimization. This software is used to investigate the relationship between blending ratios and their effects on the blends' viscosities, densities, and calorific values. This software is simple to use since it recommends the best solution for the problem, such as errors that turn out to be distant from the objectives. Essentially, this software is a simulation of a test that uses our test range to assess our project's ability to meet its objective before doing it in the actual test. This is done to minimize the expense of experiments rather than using the try and error process. Besides, this software can also improve the performance of existing processes, reliability, and performance of the mixtures. The method also generates a mathematical model of the relationships between the parameters and responses based on the data gathered from the experiments. In addition, the results obtained would be more reliable as a result of using this software.

C. Fuel Blend Formulation and Preparation

In terms of its blend formulation, sunflower oil and pentanol are the two different fuel that are blended together in different percentages ratios known as the binary biofuel blend. The mixing ratio was obtained from mixture design method to study the effects of the three key properties. The mixture design approach was utilized to construct a series of experimental runs and subsequently establish a complete prediction equation for the viscosity, density, and calorific value of a Sunflower Oil and Pentanol blend. The experiment helps to make an informed decision that evaluates both quality and cost. The developed mathematical equation then determines the best blend composition for any given viscosity and density value from the experiments that fulfil American Society for Testing and Materials (ASTM) D6751 specifications.

In this study, the binary biofuels were prepared using Pure Sunflower Oil (PSO) and the higher alcohol, Pentanol, in volumetric percentage (%). As shown in Table I, there are a total of eight mixtures samples prepared according to the volumetric percentages (%) obtained from the mixture design analysis including two neat oil samples of 100PSO and 100PEN and an additional mixture ratio 60PSO40PEN for the validation test.

Table I. PSO-PEN Blend Ratio.

	Fuel Blends (%)		
	PSO	**Pentanol**	**Nomenclature**
1	25	75	25PSO75PEN
2	50	50	50PSO50PEN
3	75	25	75PSO25PEN
4	100	0	100PSO
5	0	100	100PEN
Repetition			
6	25	75	25PSO75PEN
7	50	50	50PSO50PEN
8	75	25	75PSO25PEN
Validation Test			
6	60	40	60PSO40PEN

For the fuel blend preparation, three biofuels samples were prepared with mixing ratios of 25% (75PSO25PEN), 50% (50PSO50PEN), and 75% (25PSO75PEN) of Pentanol with PSO were prepared by using a set of measuring cylinders to measure the ratio of the blend in millilitre (ml). All blends were prepared without surfactant for a total of 300 ml where the amount is sufficient to conduct an experiment of the three key properties. The magnetic stirrer is used to rotate the magnetic stir bar to ensure that all the mixtures are completely blended.

D. Fuel Properties Testing

The physicochemical properties of PSO-PEN blends were established using ASTM and in-house standards. Three physicochemical properties were analysed which are the viscosity, density, and calorific value. These three key properties are important in developing biofuel blends because density and viscosity can affect the fuel injection pump system, and calorific value is the energy emitted from the combustion of the biofuel in the combustion chamber, ensuring mixture compatibility in compression ignition engines. As a result, ensuring that this blend works efficiently is an important part of the methodological process.

The key properties are examined according to ASTM standards. The densities (kg/m^3) of the PSO-PEN blends are determined using a 25 ml pycnometer (Gay-Lussac) following the DIN ISO 3507. While the viscosities (mm^2/s) of the PSO-PEN blends are determined using an ASTM D445 glass capillary viscometer (Cannon-Fenske). Finally, the Calorific Values (CV) of the fuel samples are determined using a Bomb Calorimeter (IKA C200) according to ASTM D240.

E. Blend Optimization and Validation

The significance of each biofuel binary blend that was constructed and analysed by using the mixture design method and determined using numerical analysis. The numerical analysis approach is a useful tool that may be applied to a composite computational equation. This optimization method is used to analyse the relationship between blending ratios and their influence on the key properties.

This optimization produces mathematical equations of the relationships between the variables and responses. Each component's and response's objective are to determine the lower and upper limits. A "desirability" function is used to assess the optimal mixture in the range to optimise the combination with all limitations. Desirability should be a number between 0 and 1. A value of one (1) indicates that the conditions were ideal, but a value of zero (0) indicates that the reactions were beyond reasonable bounds. The ideal blend composition (%) with kinematic viscosity, density, and calorific value that fulfils the ASTM D6751 criteria may be optimised due to the numerical analysis.

The validation is performed by comparing the data obtained from the mathematical equation with the experimental value obtained from the experiment of the 60PSO40PEN blend. The method must be repeated if the experimental value has a large margin of error. The project's workflow can, however, be continued if the experimental value has a small error percentage.

III. RESULTS AND DISCUSSION

A. Blend Characterization

The average result of the measurement for density, kinematic viscosity and calorific value for all the blends has been recorded in the Table II. All the measurement was repeated three times for each blend ratio to obtain an average value. In addition, all the results for blend characterization were used in the mixture design analysis.

Table II. PSO-PEN Blends Characterization Results.

Fuel Blends	**Density (kg/m^3)**	**Kinematic Viscosity (mm²/s)**	**Calorific Value (kJ/kg)**
25PSO75PEN	871.22	5.3141	35624
50PSO50PEN	897.67	8.8249	37167
75PSO25PEN	925.21	15.6567	38051
100PSO	951.84	39.3822	39600
100PEN	843.10	3.2601	34650
60PSO40PEN	911.51	11.7083	37562

For density, it shows that 100PSO has the highest density of 951.84 kg/m³ while 100PEN has the lowest result of density among all. The blend ratios of 50PSO50PEN, 75PSO25PEN and 25PSO75PEN have a density value of 897.67 kg/m³, 925.21 kg/m³ and 871.22 kg/m³, respectively. This indirectly indicates that the density of PSO has been successfully decreased by mixing it with higher alcohol, Pentanol, whose density is lower than that of PSO. For kinematic viscosity, it also shows that 100PSO has the highest kinematic viscosity of 39.3822 mm²/s while 100PEN has the lowest result of kinematic viscosity among all. The blend ratios of 50PSO50PEN, 75PSO25PEN and 25PSO75PEN have a kinematic viscosity value of 8.8249 mm²/s, 15.6567 mm²/s and 5.3141 mm²/s, respectively. A statistical study has shown that increasing the higher alcohol, pentanol percentage reduces the kinematic viscosity of the blends significantly. Finally, for calorific value it shows that 100PSO has the highest CV of 39600 kJ/kg while 100PEN has the lowest result of CV among all. The blend ratios of 75PSO25PEN, 25PSO75PEN, and 50PSO50PEN have a CV value of 38051 kJ/kg, 35624 kJ/kg and 37167 kJ/kg, respectively. As can be seen, the CV increases in direct proportion to the percentage of PSO in the blends. An increase in CV is expected to improve the combustion efficiency of the engine.

The equation of density, kinematic viscosity and calorific value was obtained numerically by utilising Design-Expert software after correlating data from the experiments. Using the mathematical equation, the software could generate the predicted response values. For given levels of each factor, the equation in terms of actual factors can be used to make predictions about the response. This equation thus can be used in any blending ratios to get the actual results. As per shown in Table III, the Eqs. (1), (2) and (3) are the equation for of fuels density, kinematic viscosity and calorific value.

The density, kinematic viscosity and calorific value are all expressed as a function of PSO and PEN, where PSO and PEN are in volumetric percentages (%). The mathematical equation developed in response to this study enables for early prediction of blending the three key properties without a significant number of sample and experimental runs. This strategy also speeds up the experiment and also helps in reducing the costs of the optimization procedure.

Table III. PSO-PEN Blends equations.

Equation	Number
$Density, \rho = 9.52022(PSO) + 8.43593(PEN)$	(1)
$Kinematic\ Viscosity, v = 0.394850(PSO) + 0.032(PEN) - 0.005005(PSO)(PEN) - 0.000042(PSO)(PEN)(PSO - PEN) - 3.14267e{-7}\ (PSO)(PEN)(PSO - PEN)$	(2)
$Calorific\ Value, CV = 395.33292(PSO) + 345.93958(PEN)$	(3)

B. Blend Optimization – Numerical Optimization

Based on the results obtained from the tests, the numerical optimization method was used to find the best mixture of parameters to satisfy each response's requirements. In this numerical optimization, lower and upper limits were specified as the objective of each component and response. The objective was to optimise the ideal blend composition (%) that fulfils the ASTM D6751 standards for density, kinematic viscosity, and calorific value. The criterion in the numerical optimization is set to meet the ASTM D6751 requirements for all of the key properties that have been tested in this study to get the most optimal blend ratio. In Table IV the constraint optimisation and desirability are both shown.

Table IV. Constraint optimization.

Name	**Constraint Optimization**		
	Goals	**Lower Limit**	**Upper Limit**
PSO	In Range	0	100
PEN	In Range	0	100
Density (kg/m^3)	In Range	843.1	951.84
Kinematic Viscosity (mm²/s)	Target = 5.99	1.9	6.0
Calorific Value (kJ/kg)	In Range	34650	39600
Desirability	1.000		

To assess the optimal mixture in the range to optimise the mixtures with all limits, a "desirability" function is used. Desirability should be a value between 0 and 1 on a scale of 1 to 10. A number of one (1) represents ideal conditions, whereas a value of zero (0) shows that the responses were out of boundaries. Figure 1 illustrates that the predicted solution had a desirability rating of 1.0, indicating that it was a nearly ideal case.

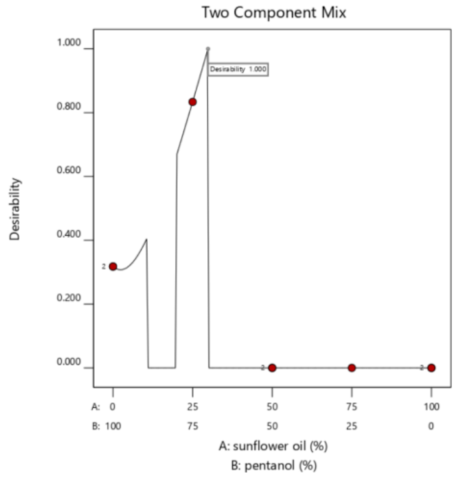

Fig. 1. The desirability of the predicted model.

From the constraint optimisation, there are three solutions presented from the Design Expert Software. Table V shows the one optimum solution given by the software compared to the ASTM D6751. The calculated optimum blend at that desirability value was 30PSO70PEN as shown in Fig. 2, which met the ASTM D6751 density, kinematic viscosity, and calorific value standards.

Table V. PSO-PEN optimise solution results

Name	Solution	ASTM D6751
PSO	29.8566	-
PEN	70.1434	-
Density (kg/m^3)	875.966	880
Kinematic Viscosity (mm²/s)	5.99	1.9-6.0
Calorific Value (kJ/kg)	36068.7	-
Desirability	1.000	-

The predicted density, kinematic viscosity, and calorific value for the 30PSO70PEN mixture are 875.966 kg/m³, 5.99 mm²/s, and 36068.7 kJ/kg, respectively. As a result of the numerical study, the optimal blend composition of 30PSO70PEN was predicted, which meets the standards' requirements. The desirability of the solution obtained in this study is from the models that comply to the constraints optimisation objectives that have been set.

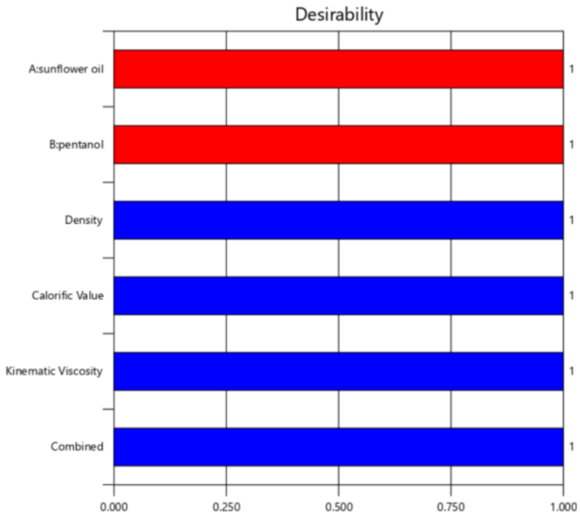

Fig. 2. Solution 1 desirability graph.

C. *Validation Results*

The validation is performed by comparing the mathematical equation given by the Design Expert Software with the experimental value obtained from the experiment of 60PSO-40PEN blend. The 60PSO-40PEN blend is measured to validate the accuracy of the experimental results. From the optimization method, three equations have been developed by the software to calculate the three key properties actual results. The actual equations for the validation results are as in Eqs. (1), (2) and (3). In every experiment that has been conducted before, 60PSO-40PEN blend ratio of PSO-PEN blend has also been tested for all the three key properties.

The 60PSO-40PEN blend was prepared to validate the equations derived from the mixture design. The density, kinematic viscosity, and calorific value of this new blend were calculated using equations provided by the mathematical equation in the Design Expert Software, then compared to experimental data. The difference between experimental and calculated values was in the range of 0.012 to 7.14 %, as shown in Table VI. As a result, the numerically derived equations are considered valid and reliable.

Table VI. Validation results.

Property	Experimental Results	Theoretical Results	Error (%)	Commercial Diesel fuel
Density (kg/m^3)	911.51	909.11	0.315	822-880
Kinematic Viscosity (mm²/s)	11.7083	10.98	7.14	3-4
Calorific Value (kJ/kg)	37562	37557.56	0.012	42700 - 44800

IV. CONCLUSION

Based on the result obtain from the experiments, the mathematical equation of each key properties was developed using a mixture design technique to estimate and optimise the responses of various PSO-PEN blend ratios. The calculated values indicate a difference between experimental outcomes of 0.012 % and 7.14 %, indicating that the generated equations are considered valid and reliable. According to the ASTM 6751 standard for biodiesel fuels, an ideal mixture of 30PSO70PEN is made to fulfil the fundamental of these three main properties. The ideal blend of PSO-PEN has been identified as a new potential source of renewable biofuel, according to these studies. However, although density, kinematic viscosity, and calorific value are the three most important fuel variables to consider when analysing IC engine characteristics, there are more fuel characteristics that need to be consider as well. Consequently, the three major properties obtained from these experiments have been considered to meet the study's objectives.

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Hazim Sharudin: Conceptualization, Writing – Original Draft Preparation; Sharzali Che Mat: Writing – Review & Editing; Rozaini Othman: Design and Methodology, Nur Irsalina Huda Nazri: Data Collection, Muhammad Arif Ab Hamid Pahmi: Project Supervision, Azmi Husin: Project Administration, Noor Iswadi Ismail: Data Analysis and Mahamad Hisyam Mahamad Basri: Data Validation.

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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