LINEAR REGRESSION

An Application of Linear Regression in Modeling and Optimization for Biodiesel Production from Commercially Available Oleev Active Waste Cooking Oil

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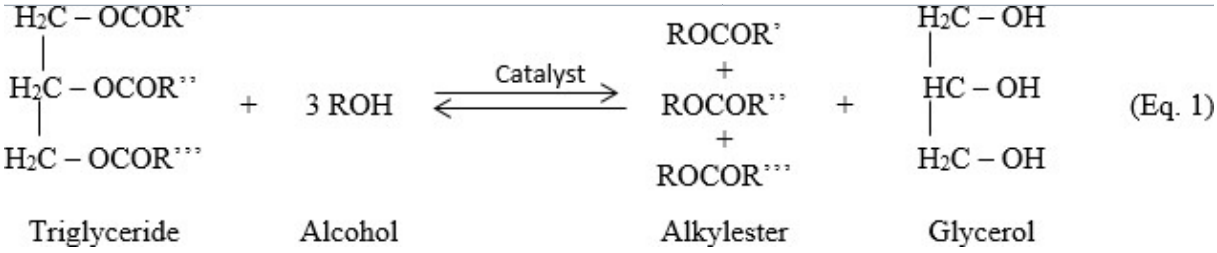
Abstract

Biodiesel, a renewable and environmentally friendly alternative to conventional diesel fuel, has garnered significant attention due to its potential to address pressing energy and environmental challenges. Biodiesel is a type of biofuel that is produced by the transesterification of organic resources, usually vegetable or animal fats or recycled cooking oils. In this method, alcohol and a catalyst are used to chemically transform these feedstocks into glycerol and biodiesel. Either pure biodiesel (B100) or blended with petroleum diesel (e.g., B5, B20) can be used as a drop-in replacement for traditional diesel fuel. The ability of biodiesel to be used with current diesel engines and infrastructure makes it easy to adopt without requiring major changes. This work effectively modelled and optimized biodiesel production from waste cooking oil (WCO) using linear regression to evaluate the impact of operating factors on yield response. Yield records and physicochemical constants of the produced biodiesel were affected by free factors, specifically the following: reaction temperature (45 to 65 °C), catalyst concentration (0.5 to 1.5 wt.%), reaction time (15 to 45 min), and methanol/oil mole proportion (3:1 to 15:1). Optimal conditions for biodiesel production were found to be methanol-to-oil molar ratio of 15:1, catalyst concentration of 0.5 wt.%, reaction period of 45 minutes and reaction temperature 45^0C resulted in a yield of 96.8%.

Keywords: Biodiesel; Feedstock; Biofuel; Optimization; WCO; Transesterification

1 Introduction

Biodiesel is an alkyl ester of fatty acids that is made from biological sources such algae, vegetable oil, and animal meat waste. Biodiesel made from renewable resources is regarded as the most significant type of biofuel. Acid-catalyzed transesterification, alkaline-catalyzed transesterification, enzyme-catalyzed transesterification, and non-catalyzed supercritical methanol are the four categories of transesterification processes. Because it is the quickest reaction, has a greater yield, gentle reaction conditions, is inexpensive, less corrosive, and less poisonous, the alkaline catalyzed transesterification method was employed in this work [1]. The process of transesterification involves replacing an alcohol's organic group (alkyl) with a triglyceride's organic group. Transesterification processes are done with use of a catalyst either an acid or a base catalyst. The use of enzymes can result in transesterification. The transesterification reaction is depicted in Equation 1.



About 90–98% of the total mass of vegetable oils is made up of triglycerides.

When triglycerides and alcohol combine under specific conditions—such as time, temperature, mixing rate, and catalyst presence—a mixture of fatty acids, alkyl esters (biodiesel), and glycerol is produced. This process is known as transesterification. The primary alcohols that can be utilized in a transesterification reaction are methanol, ethanol, and butanol. There are three main stages in alkaline catalyzed transesterification: the first is feedstock treatment, which entails determining the amount of free fatty acid in the feedstock, eliminating insoluble contaminants, and removing water. The alkaline transesterification process, which is the second phase, involves adding alcohol and a catalyst to the oil at a specific temperature and mixing rate for a predetermined amount of time. Biodiesel treatment, which comprises water washing, water removal from the produced biodiesel, and biodiesel purification, is the last stage of the transesterification process. The ratio of methanol to oil, catalyst concentration, temperature, and time are some of the several variables that impact the manufacture of biodiesel [3]. This work uses linear regression analysis to examine the impact of each component on the final yield since it enables the use of a small number of tests to cover a large number of variables. To examine the results, the linear regression method was employed. The biodiesel that is produced has established specifications and can be mixed with diesel engines.

Biodiesel is an alternative fuel that may power diesel engines and is produced from leftover cooking oil, vegetable oil, or animal fat. They can be generated on a big scale in an industrial setting or domestically using waste and organic materials. Animal fats, algae lipids, or vegetable oil are used to make them. Methanol is the primary alcohol used in the manufacturing of biodiesel, hence the term “methyl ester” for biodiesel. However, it can also be produced using other alcohols, such as ethanol.

Regression analysis is a process to determine a mathematical relationship between dependent and independent variable. It is accomplished by making adjustments in a regression equation. Both linear and non-linear forms of this equation are possible. Regression analysis can be performed using a variety of software programs, such as the MS Excel data analysis tool set. Generally speaking, the regression equation curve may or may not fit all data sets. Residual is the difference between the actual data and the value that the regression equation yielded under the identical set of conditions. Regression analysis is crucial to the manufacture of biodiesel because it allows one to use the regression equation to calculate the yield response of biodiesel from any set of data without the need for the transesterification process. It can also be used to compare the projected yield response from the regression equation with the experimental yield response utilizing the transesterification process [5]. Any sustainable biomass that is intended to be converted into energy to create fuel or utilized directly as fuel is referred to as a feedstock.

Commercially available Oleev Active waste cooking oil has been chosen as the feedstock for this project.

2 Methodology

Transesterification is a chemical procedure that converts triglycerides (fats) in oils into biodiesel. Triglycerides from oils are utilized as a feedstock for biodiesel manufacturing. Research suggests that biodiesel produced by transesterification can be combined with petroleum diesel to power diesel engines due to their similar qualities. Chemical-catalyzed transesterification is widely used in industry due to its ease of usage, high conversion rate, and short processing time. The chemical equation for transesterification reaction is presented below

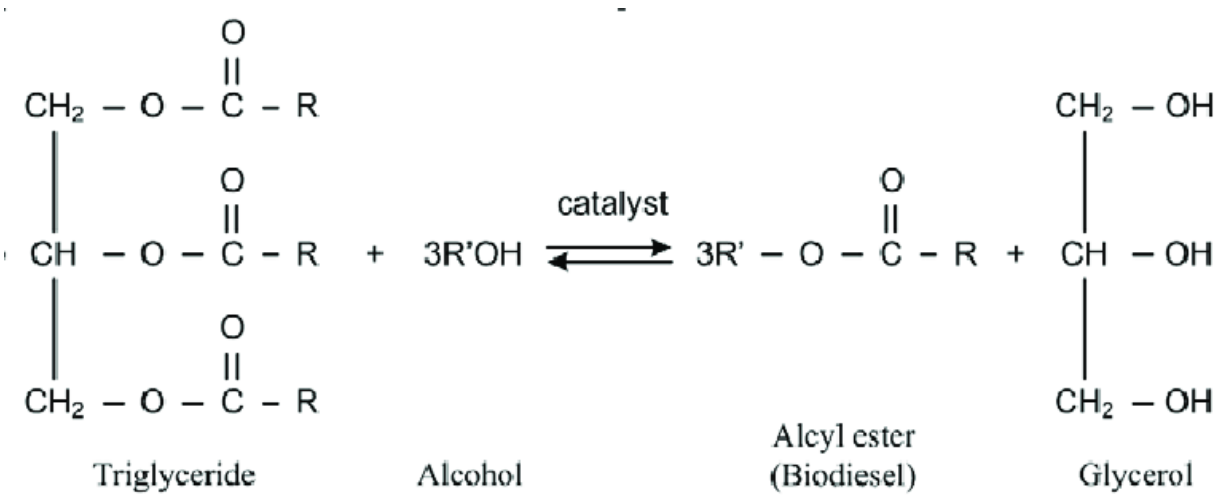


Figure 1. Chemical equation for transesterification process.

In this project, transesterification will be performed on waste cooking olive oil, and the process will be optimized for biodiesel yield. The proper setup of process parameters will aid in getting a higher yield fast from the available limited feedstock and resources, resulting in a cost-effective production.

3 Design strategy

3.1 Taguchi method of quality control

Genichi Taguchi, a Japanese engineer and statistician, developed the Taguchi method while working on a telephone switching system for the Electrical Communication Laboratory in Japan. He wanted to use statistics to improve the quality of manufactured goods.

The Taguchi quality control technique is an engineering strategy that emphasizes the role of R&D, product design, and development in eliminating errors and faults in manufactured goods. To reduce variation in a process, the Taguchi technique adopts a robust experimental design. The method's ultimate purpose is to provide the producer with a high-quality product at a low price [8].

This project adheres to Taguchi's experiment design. The Taguchi method relies on orthogonal array experimentation. Orthogonal arrays provide a collection of well-balanced experiments that can be run to achieve the best results. This strategy optimizes process design to improve product quality while lowering costs. The Taguchi technique is an eight-step procedure that considers planning, conducting, and assessing results to determine the most appropriate amounts of control parameters. The steps are as follows:

1. To identify the main function, side effects, and failure mode.
2. To identify the noise factors, testing conditions and quality characteristics.

3. To identify the objective function to be optimized.
4. To identify the control factors and their levels.
5. To select the orthogonal array matrix based on degrees of freedom.
6. To conduct the matrix experiment.
7. To analyze the data, predict the optimum levels and performance.
8. To perform the verification experiment and plan the future action.

3.2 Determination of control factors

Based on literature review the following four factors each at three different levels have been selected for the experiment.

Table 1. Control factors with their levels for yield.

Factors		Levels		
Low (1)	Medium (2)	High (3)		
A	Methanol to Oil Molar Ratio	3:1	9:1	15:1
B	Catalyst amount (wt./wt.%)	0.5	1	1.5
C	Reaction Time (min)	15	30	45
D	Reaction Temperature (^{0}C)	45	55	65

3.3 Minimum number of experiments to be conducted and selection of orthogonal array

The total no of experiment to be performed is given by the formula

$$\text{No. of experiments} = L^f \tag{1}$$

where L = number of levels and f = number of factors.

However, as the number of levels and components increases, so does the overall number of experiments require. This raises the cost of production and the time necessary to do it, making the process more tiresome. The degree of freedom, as given by the formula, determines the order of the orthogonal array (i.e., the total number of experiments to be done).

$$\text{DOF} = f(L-1) + 1 \tag{2}$$

For the chosen four factors at three different levels,

$$\text{Total DOF} = 4(3-1) + 1 = 9 \tag{3}$$

The order no of orthogonal array, n ≥ total DOF Therefore n ≥ 9

Since OA_9 is available, so it has been selected for the experiment runs. The standard orthogonal array OA_9 is represented in the following way: -

Table 2. Design of experiment using L9 orthogonal array.

RUN	PARAMETER			
A	**B**	**C**	**D**	
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.4 Experimental runs and data collection

For the selected four factors (A, B, C, D) and the three different levels (1, 2, 3), the orthogonal array table is shown below.

Table 3. Experimental observations with percentage yield.

Sl. No.	Methanol to Oil Molar Ratio (A)	Catalyst Amount (%wt) (B)	Reaction Time (mins) (C)	Reaction Temperature (^{0}C) (D)	Yield Percentage (%)
1	3:1	0.5	15	45	55
2	3:1	1.0	30	55	42
3	3:1	1.5	45	65	40
4	9:1	0.5	30	65	72
5	9:1	1.0	45	45	86
6	9:1	1.5	15	55	74
7	15:1	0.5	45	55	96
8	15:1	1.0	15	65	76
9	15:1	1.5	30	45	88

4 Results and discussion

4.1 Regression analysis

Regression analysis is a statistical process that determines the relationship between a dependent and independent variable. The most popular type of regression analysis is linear regression, which involves fitting data sets to a line. It is mostly used for prediction and forecasting, as well as comparing experimental and anticipated data sets under various specified conditions. In linear regression, the dependent variable (Yi) is represented as a linear combination of the independent

variables (Xi). For example, given four independent variables and a dependent variable (Yi), the linear regression model takes the form of a straight-line equation as follows:

$$Y_i = \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip} + \varepsilon_i \quad (4)$$

where Yi is the yield percentage, xij is the value of the jth independent variable for run i, βj is the coefficient of variable j and εi is the error term (difference between the true and predicted values).

The primary goal of regression analysis is to generate a regression model equation and determine the relevance of independent variables on the dependent variable. The least squares (R^2) approach is a mathematical methodology for determining the regression line that best fits a given data set. When R^2 approaches unity, the regression model is better fitted.

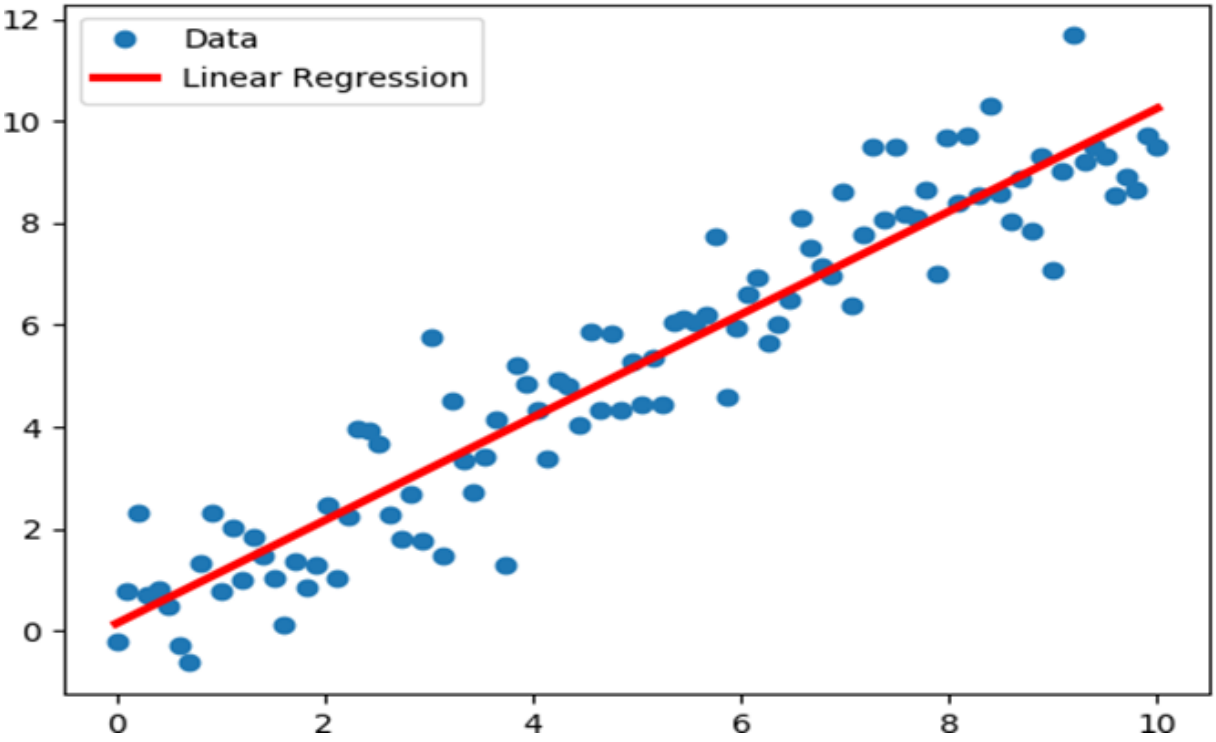


Figure 2. Linear regression analysis model curve.

Comparison of experimented and predicted yield (in %) of the nine treatment conditions is tabulated below-

Table 4. Comparison of biodiesel yield in percentages.

Observations	Experimental yield %	Predicted yield %	Residuals
1	55	56.9	-1.9
2	42	49.4	-7.4
3	40	41.9	-1.9
4	72	66.6	5.4
5	86	79.6	6.4
6	74	63.6	10.4
7	96	96.7	-0.7

Observations	Experimental yield %	Predicted yield %	Residuals
8	76	80.7	-4.7
9	88	93.7	-5.7

The experimented yield is the real yield resulted from applying the different reaction conditions while the predicted is resulted from inserting reaction conditions in the MS Excel tool pack.

Finding the regression model equation, indicating the importance of each variable, and identifying the ideal elements that produce the best yield are the objectives of the regression analysis. In regression analysis, the coefficient R^2 shows how well the model fits the data; the closer R^2 is to unity, the better the regression model fits the data. For this model, the R^2 value was found to be 0.908. This number guarantees the regression model's proper fitting and validates its suitability.

Table 5. Regression statistics.

Regression Statistics	
R Square	0.908
Adjusted R Square	0.815
Multiple R	0.953
Standard Error	8.625
Observations	9

Table 6. Analysis of experiments on MS Excel tool pack.

	Coefficient	Std. Error	t Stat	p-value
Intercept	78.0556			
Methanol to oil molar ratio	3.4167	0.5869	5.822	0.0043
Catalyst amount	-7.0000	7.0422	-0.994	0.3765
Reaction time	0.1889	0.2347	0.805	0.4661
Reaction temperature	-0.6833	0.3521	-1.941	0.1243

The linear regression equation is: -

Biodiesel yield (%) = 78.0556 + (3.4167 × Methanol to oil molar ratio) - (7.0000 × Catalyst amount) + (0.1889 × Reaction time) - (0.6833 × Reaction temperature)

According to Table 6, the model provides a good estimate of the response for the design over the ranges that are investigated, and the data is reasonably fitted. The disparity between the expected and experimental response is known as residual. A good fit between the experimental findings and the projected values is confirmed by Table 4, which displays the relationship between the residuals and the predicted response. The actual values within the red dots are almost exactly in line with the lines representing the predicted values.

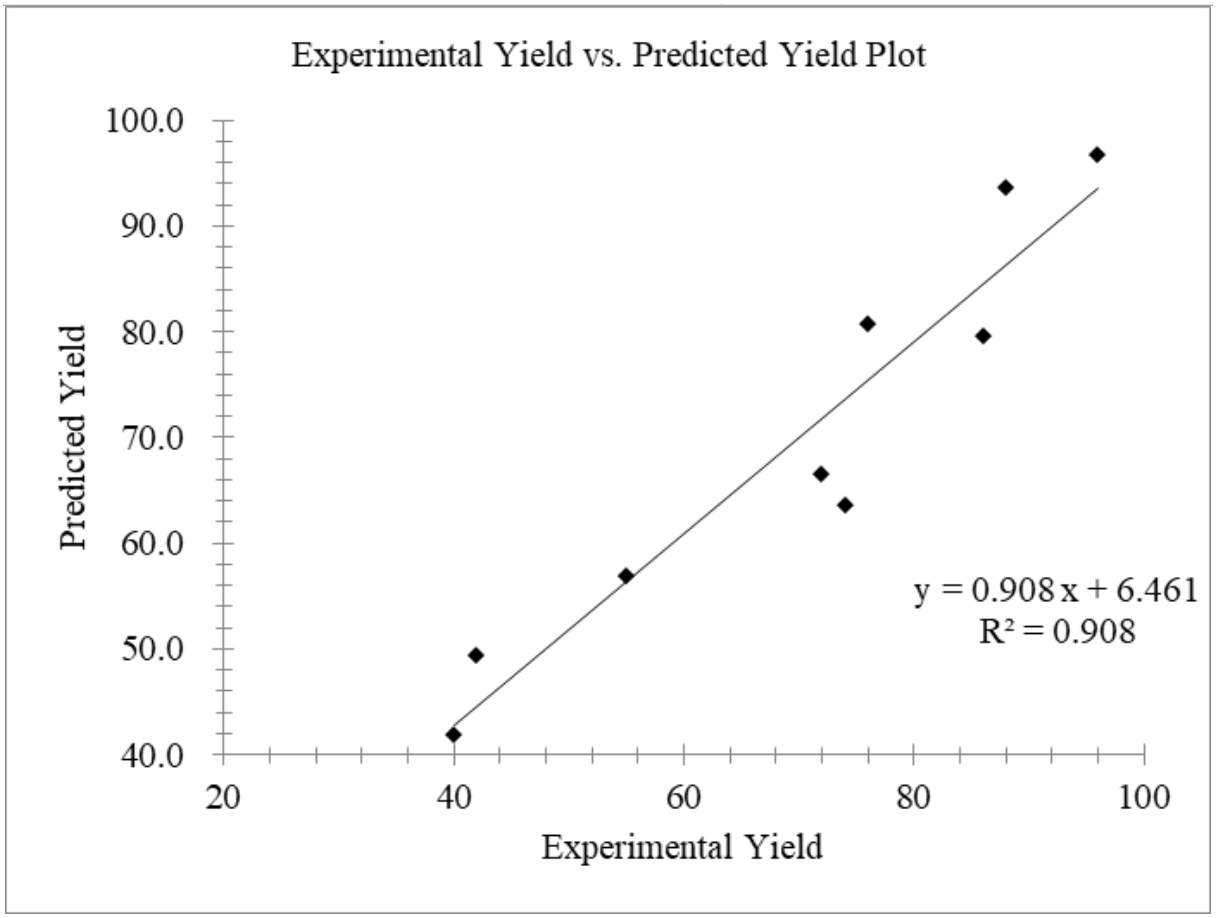


Figure 3. Relation between experimented and predicted response.

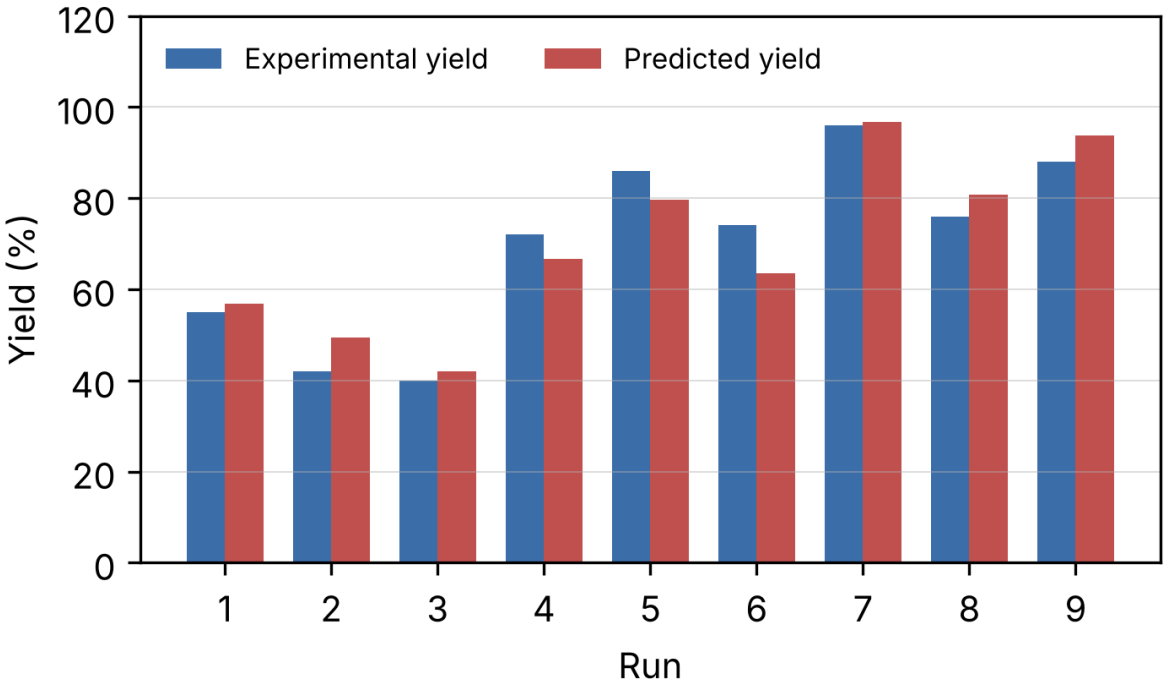


Figure 4. Comparative analysis plot of experimental and predicted yield.

4.2 Validation of the optimal setting by average performance graph

To determine the best combination of biodiesel production processing parameters for improving yield, the average of yield outputs for each biodiesel parameter level is computed using the Taguchi method's primary effect analysis. This procedure is carried out by sorting the yield responses corresponding to the levels of the biodiesel production parameters in each column of the OA and then taking the average of parameters with the same levels.

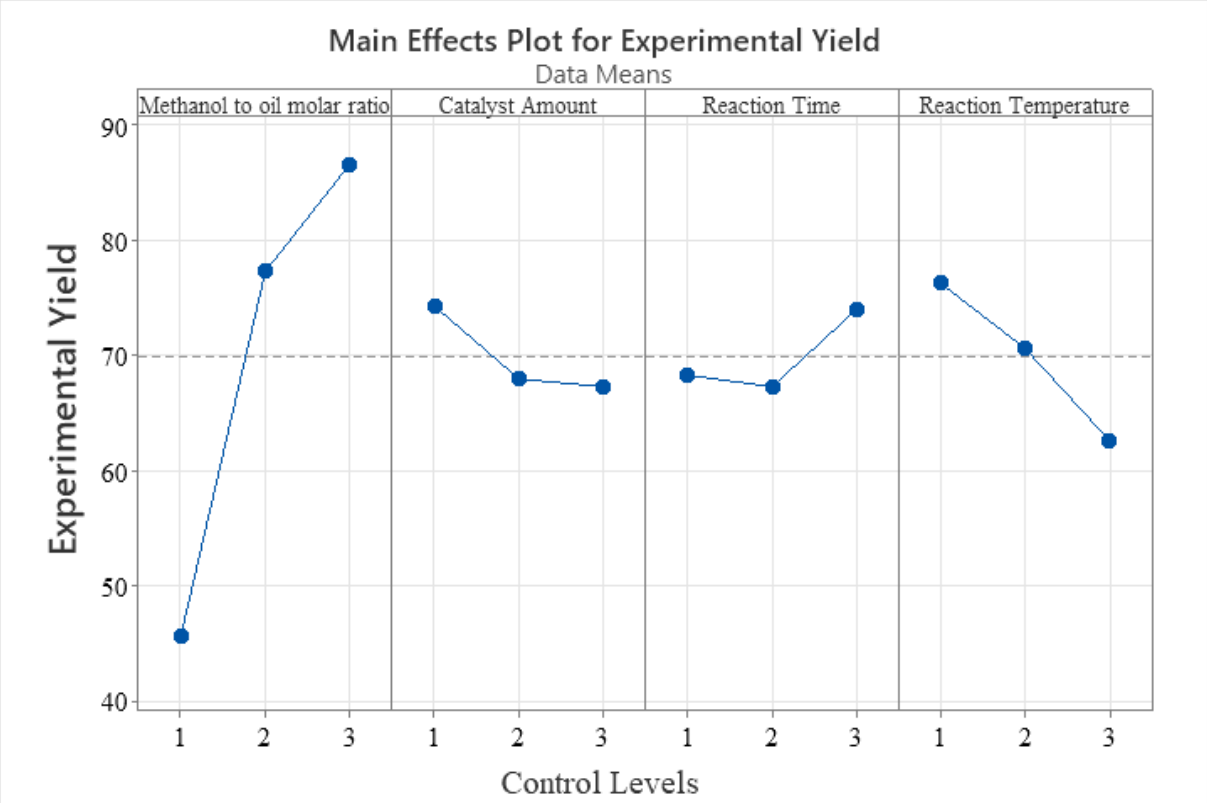


Figure 5. Average performance graph for yield responses.

A3, B1, C3, and D1 have the highest average yield responses for variables A, B, C, and D respectively. The optimal parameter settings for greatest yield are anticipated as A3, B1, C3, and D1. The optimal parameters occur under the following conditions: **Methanol-to-oil molar ratio of 15:1, catalyst concentration of 0.5 wt.%, and reaction period of 45 minutes and reaction temperature 45^{0}C.**

4.3 Confirmation run of the optimal setting

To validate the above optimal setting a confirmation run was being carried out. The confirmation run that was performed is as shown in table 7.

Table 7. Confirmation run for optimal setting.

Best combination				**Yield of Biodiesel (%)**
Methanol-to-oil molar ratio	Catalyst concentration (wt.%)	Reaction time (min)	Reaction Temperature (^{0}C)	
15:1	0.5	45	45	96.8

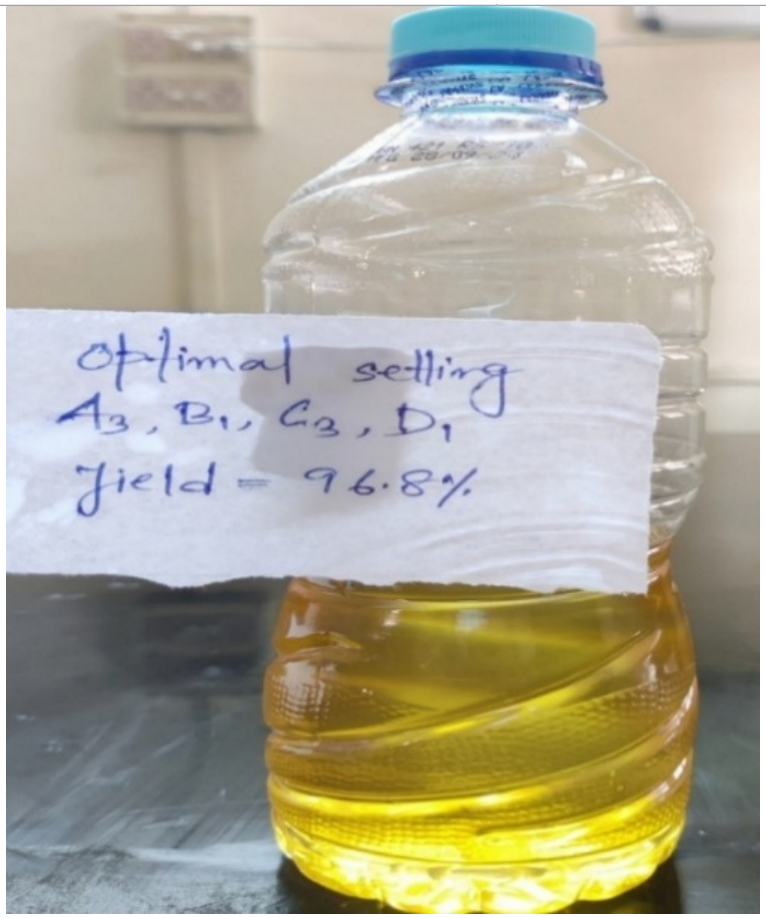


Figure 6. Produced biodiesel by optimal setting.

4.4 Discussion on optimal setting of process parameters

The study indicated that the best methanol-to-oil molar ratio is 15:1. This molar ratio is commonly used to achieve optimal yield percentage for biodiesel in a given context. Adding more methanol than required can reduce yield response. Excess methanol interferes with the separation of methyl ester and glycerol by increasing glycerol solubility.

The catalyst concentration was determined to be best at 0.5% (wt/wt). This suggests that using a medium amount of catalyst in the process can improve fuel quality.

The optimal reaction time is 45 minutes. Reaction time is critical for producing biodiesel and determining its qualities, including calorific value and cetane number. The study indicated that a 45-minute reaction time produced the purest biodiesel compared to shorter or longer reaction times. Excess reaction time can reduce the quality of biodiesel by producing backward transesterification, leading to loss of esters and soap formation.

The optimal temperature for the reaction is found to be 45°C. This temperature is critical for producing biodiesel. Maintaining a steady reaction temperature throughout the process improves the grade of biodiesel produced. The higher temperature accelerates the saponification of triglycerides. However, excessively high temperatures can harm the conversion process.

The best configuration maximizes the yield of biodiesel.

4.5 Significance of process parameters for yield response from ANOVA

Analysis of variance (ANOVA) is a statistical procedure that divides observed aggregate variability within a data set into two parts: systematic and random variables. The systematic factors have a statistical impact on the supplied dataset, but the random factors do not. In a regression research, analysts employ the ANOVA test to examine how independent factors influence the dependent variable.

Table 8. Significance of process parameters for yield response from ANOVA.

Factors	Coefficient	P-value	Status	Remark
Methanol to oil molar ratio	3.4167	0.0043	<< 0.05	Highly significant
Catalyst amount	-7.0000	0.3765	>>0.05	Non statistically significant
Reaction time	0.1889	0.4661	>>0.05	Non statistically significant
Reaction temperature	-0.6833	0.1243	>>0.05	Non statistically significant

ANOVA analysis is used to determine which components are significant when manufacturing biodiesel utilizing the transesterification process. The significance of each component is established by the p-values displayed in the table. If the p-value for one component is less than 0.05, the factor is considered highly significant. If a factor's p-value is close to, somewhat more than, or less than 0.05, it is statistically significant. When the p-value for a factor exceeds 0.05, the factor is not significant. The only component that is highly significant is the methanol to oil molar ratio. Reaction temperature, the reaction time and catalyst concentration are unimportant in terms of yield. Table 8 summarizes the significance of each element. Each factor's significance and impact are thoroughly explored.

4.6 Effect of methanol to oil (M:O) molar ratio

Methanol is an essential reactant because it combines with triglycerides to form methyl ester (biodiesel). Excess methanol requires more equipment and power. A high methanol percentage increases the glycerol, which slows the reaction and results in a lower biodiesel output. The presence of methanol in the final output is undesirable since 1% methanol in the produced biodiesel can lower its flashpoint. A high yield percentage was attained in the treatment conditions with a molar ratio of 15:1. As demonstrated in Table 8, the effect of M:O is very significant for the reaction, with a p- value of 0.0043.

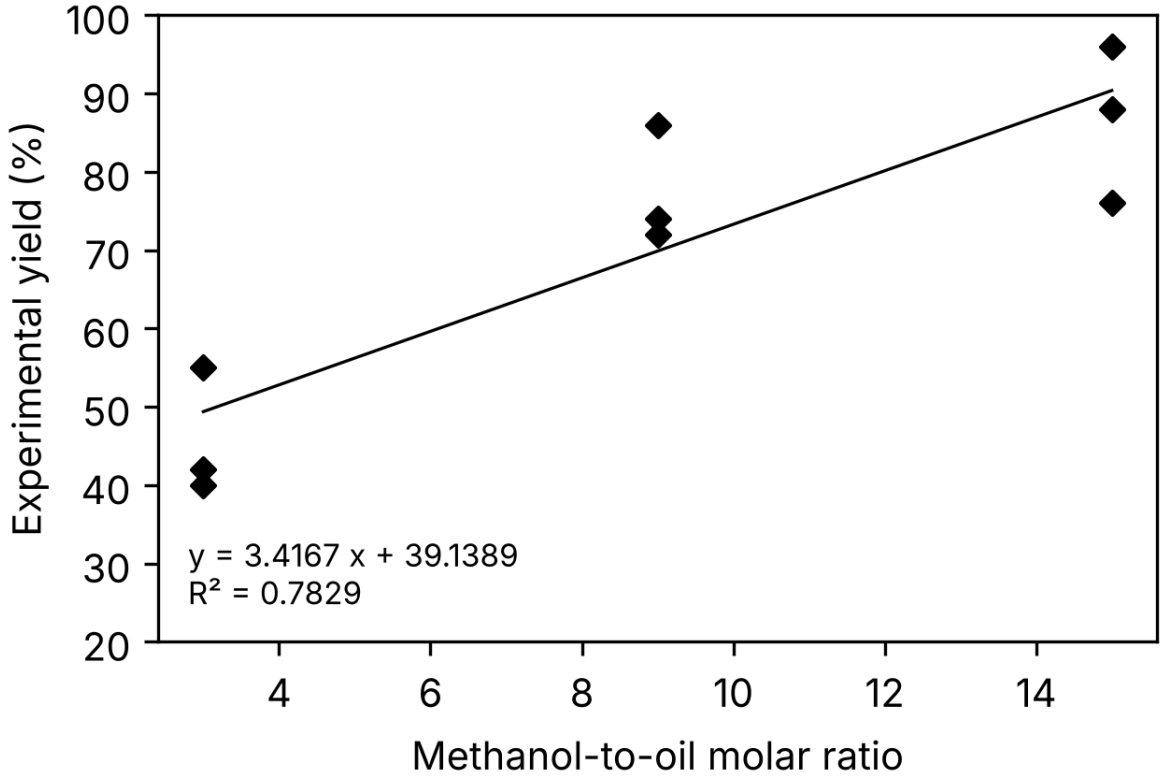


Figure 7. Scatter plot of yield percentage vs. methanol to oil molar ratio.

4.7 Effect of catalyst amount

A catalyst is a chemical that is necessary to speed up the reaction but is not consumed throughout the process. In the absence of catalytic conversion, waste cooking olive oil must be converted into biodiesel at high temperatures for an extended period of time. The catalyst utilized was potassium hydroxide (KOH). Rising catalyst weight will enhance biodiesel production and improve its qualities, but only to a limited extent because rising beyond a certain point would have an irreversible effect on final yield and properties. Excess catalyst causes soap formation, reduces biodiesel yield, and changes the characteristics of the biodiesel produced. Low catalyst concentration decreases the reaction rate and reduces the yield obtained at a given time. Figure 9 illustrates how varying catalyst amounts affect yield %.

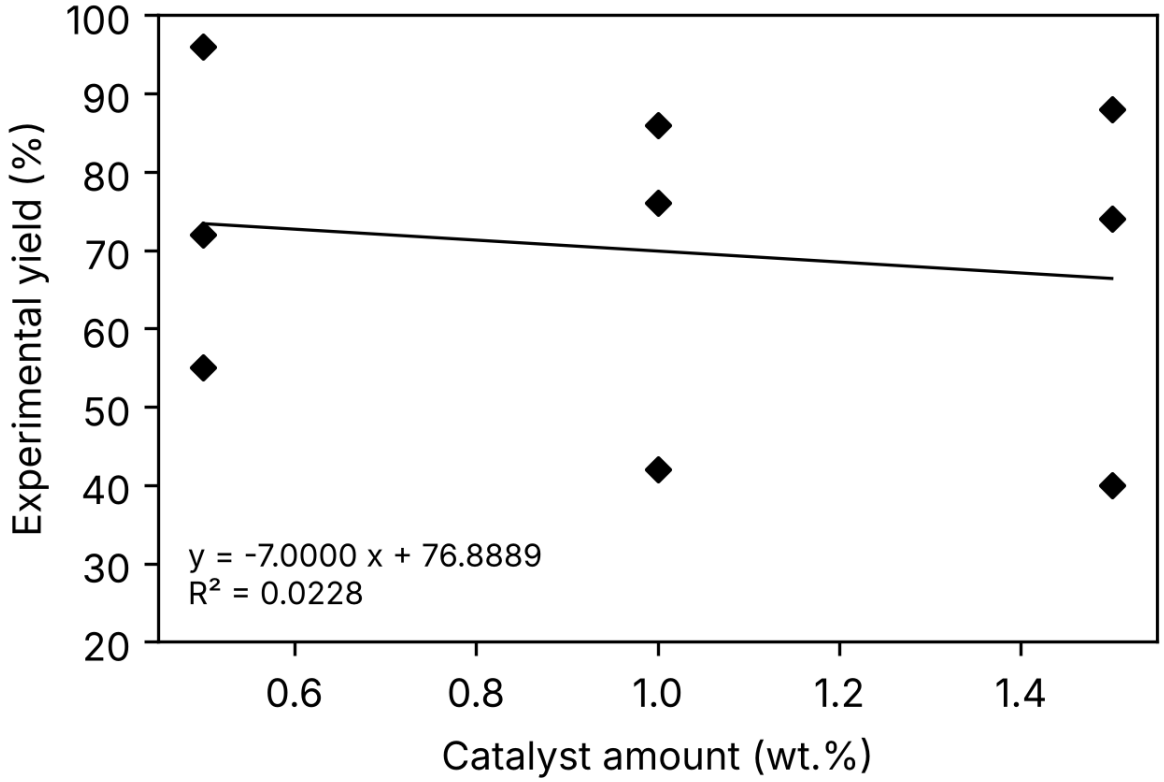


Figure 8. Scatter plot of yield percentage vs. catalyst amount.

4.8 Effect of reaction temperature

Reaction temperature is required to improve reaction rate, although the reaction temperature should be lower than the boiling point of methanol (65°C). So, if the reaction temperature above the boiling point of methanol, it will evaporate. As a result, one of the reactants may be lost, causing the reaction to be badly affected. As a result, biodiesel yield will fall, while production costs will increase. The temperature of the reaction should not be too high or too low, as any reactant requires heat to activate its molecule and collide with other molecules. Figure 10 shows that the maximum yield was obtained at 55°C when all other conditions were favorable.

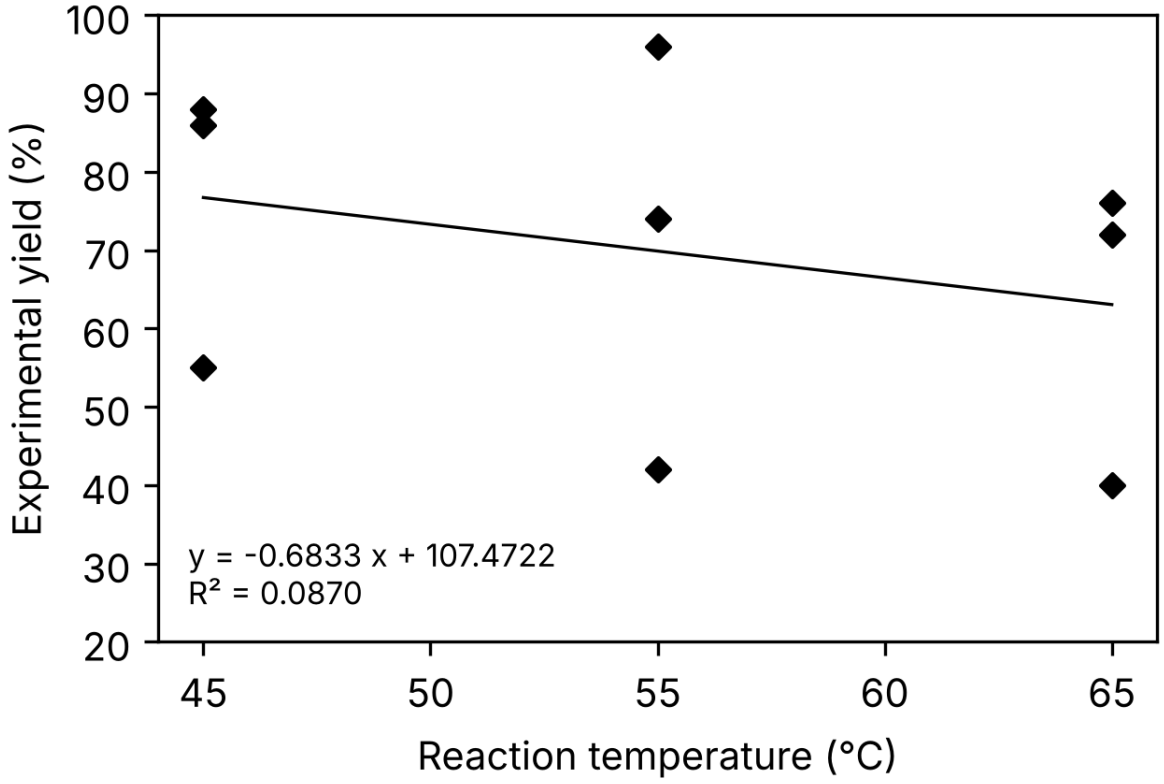


Figure 9. Scatter plot of yield percentage vs. reaction temperature.

4.9 Effect of reaction time

Increasing reaction time has the opposite effect on yield since it causes setback reactions, which reduce yield and manufacturing costs. A short response time does not allow the molecules to collide, resulting in less biodiesel production. Table 8 shows that the effect of reaction time is less significant, with a p-value somewhat greater than 0.05.

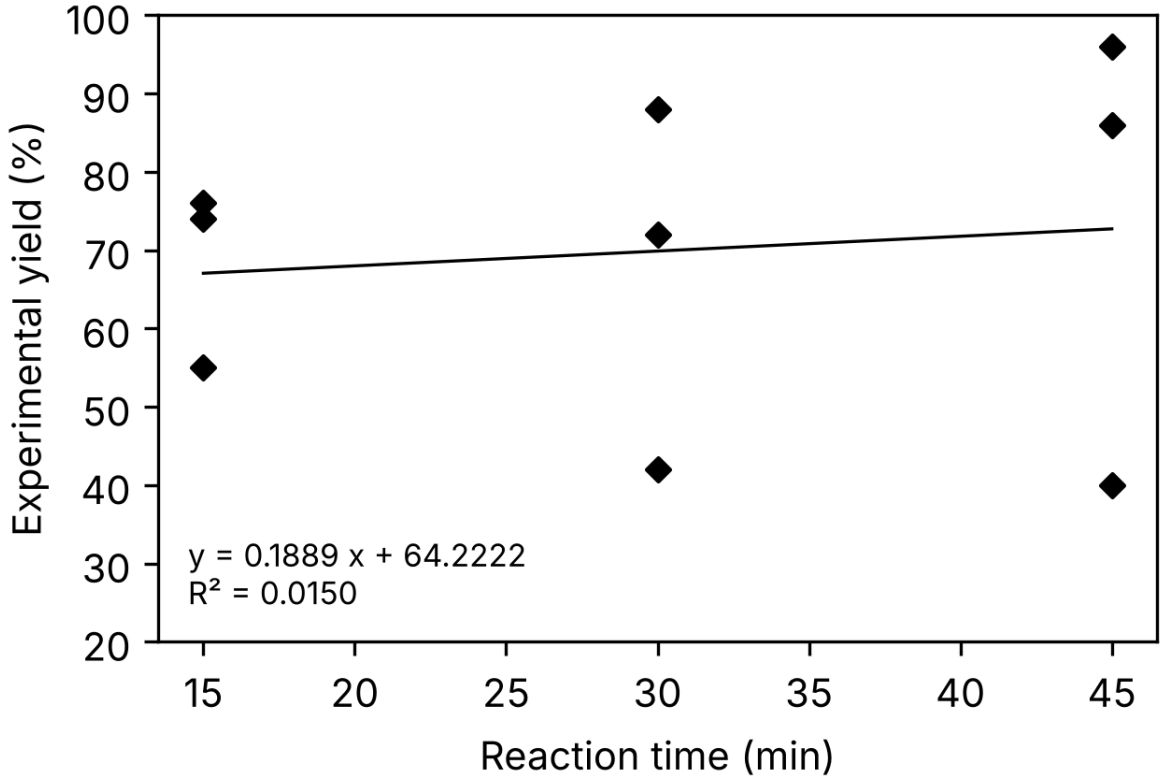


Figure 10. Scatter plot of yield percentage vs. reaction time.

5 Conclusion

Biodiesel has recently received a lot of attention across the world for its potential use as a replacement for conventional diesel in diesel engine applications. In this study, an exhaustive literature review was conducted to evaluate the current situation regarding the opportunities and obstacles of using biodiesel. The experimental and anticipated yield percentages of biodiesel generation from waste cooking olive oil were compared using linear regression analysis. The physicochemical features of olive oil biodiesel have also been identified.

The studies were carried out under the following conditions: methanol to oil molar ratio from 3:1 to 15:1, catalyst amount from 0.5 to 1.5, reaction temperature from 45°C to 65°C, and reaction time from 15 minutes to 45 minutes. The regression data show that the R-squared value is 0.908. As a result, approximately 90.8% of the data set fits into the established regression model for biodiesel yield response to waste cooking olive oil. The levels of the parameters in which yield of WOCO biodiesel can have an optimum value are- methanol to oil molar ratio 15:1, catalyst concentration 0.5%, reaction time 45 (min) and reaction temperature 45°C. A confirmation run was carried out to validate the obtained optimal condition and the value achieved where the yield was 96.8%. The Analysis of Variance (ANOVA) for yield response revealed that the methanol-to- oil molar ratio has a substantially positive statistically significant effect, whereas the reaction temperature, reaction time and catalyst concentration has no statistically significant effect on biodiesel yields.

5.1 Scope for future work

The present work can be extended with following aspects-

- The control factors in transesterification can be adjusted. The stirring speed can also be used as a control factor in the process.
- Waste olive cooking oil biodiesel can be produced in large scale production which will be cost efficient.
- Create a hybrid biodiesel by blending waste olive cooking oil biodiesel with additional feedstocks.
- Study the interactions between factors.

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