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Sustainable Utilization of Solid Waste in Biofuels Production

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Abstract*:* Many industrial sectors generate different forms of solid waste that threaten the environment. The slag of the Basic oxygen furnace, which is considered in the steel industry as a by-product, is one of these solid wastes. The main aim of this study is Using this solid waste to be included in applications related to chemical engineering. The process of producing of the biodiesel would be the main use of this waste in this study. As it is known that the energy is essential for survival of human being, most of the sources of energy used worldwide are non-renewable sources and are produced as products from oil, coal, petroleum and natural gas, also their use impact on the environment is negative. As these resources will soon run out, the sources of renewable energy should take place as replacement. Mainly the aim of this paper is biodiesel production, which is a renewable, clean, diesel with high cetane numbers, Waste cooking oil was used as the feedstock and the basic oxygen furnace slag as the catalyst beside using the methanol in a transesterification reaction. With respect to the data that come out from the experimental work, the yield of biodiesel produced could reach 90.16% if the optimum parameters for this reaction is used which states that the methanol to oil ratio should be 20:1, while the catalyst loading should be 5%, also the temperature of the reaction should be 57ºC, in addition to a 750rpm stirring rate, and the reaction time to be one hour.

Keywords: Biodiesel; Solid waste; Slag; Renewable energy.

I. INTRODUCTION

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Energy is the source of life; it could be defined as the ability of a body to make a change or do work [1].

At the moment, we rely heavily on fossil fuels, which are a non-renewable source of greenhouse gas emissions and air pollution. Since biodiesel first production in the early 1990s, its output has steadily increased [2]. Nowadays, Germany is regarded as the top producer of biodiesel [3]. The advantage of using biodiesel instead of diesel fuel is that it could be obtained from vegetable oils or animal fats which categorize it as renewable fuel. The degradation of biodiesel is faster than that of diesel fuel and also it is less toxic than diesel fuel. [4].

Vegetable oil is a fluid of high viscosity and in order to solve this problem during the reaction, micro-emulsion can be formed either by adding surfactants, ester with co-solvent or alcohols and cetane improver to the vegetable oil [5]. The required viscosity for diesel engines could be obtained by the micro-emulsions by some alcohols such as hexanol, butanol, and octanol and some solvents such as ethanol and methanol [6]. Using animal fats or vegetable oils, biodiesel could be produced through the transesterification process, which is the most commonly used method. In this reaction, triglycerides are converted into a mixture of fatty acid methyl esters (FAME), which constitute biodiesel. The process requires purification to obtain the final biodiesel product. Since the reaction is slow, a catalyst is used to enhance its efficiency. Glycerol, as a by-product is generated during this process. Several variables influence the transesterification reaction, including time and reaction temperature, the molar ratio of alcohol-to-oil, mixing speed (RPM), feedstock type, catalyst concentration, and catalyst type [4]. The below figure shows the transesterification reaction.

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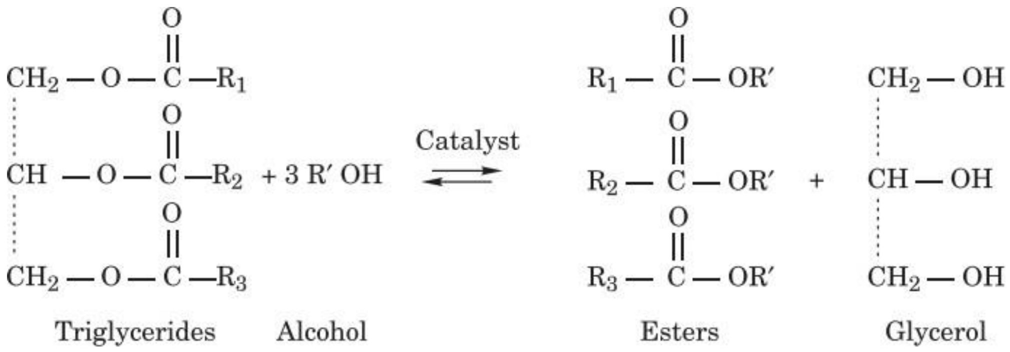

Figure 1: Transesterification reactions of triglycerides [2]

The transesterification reaction is the core process in biodiesel production, where a mixture of esters is formed. To produce biodiesel that meets international specifications and standards, several essential steps must be followed: treatment of raw material, the mixing between alcohol and catalyst, the chemical reaction itself, reaction products separation, and products purification. Once the chemical reaction is complete, the ester and glycerol phases separate. The ester mixture must then undergo purification to remove contaminants and ensure the final product meets quality standards. The transesterification reaction occurs when the catalyst dissolved in alcohol solution is mixed with oil under specific conditions. Several factors influence the efficiency of this reaction, including temperature, reaction time, mixing speed, catalyst concentration, and the methanol-to-oil ratio. Temperature plays a crucial role, as higher reaction temperatures reduce reaction time by lowering oil viscosity and increasing the reaction rate. However, excessive heating increases production costs due to higher energy consumption and may also degrade chemical compounds in the reaction. Studies suggest that the optimal reaction temperature ranges between 50°C and 60°C [5].

The conversion rate of free fatty acids is directly proportional to reaction time, but after a certain point -typically around 90 minutes- biodiesel yield no longer increases [5]. Continuous stirring is also essential for effective mass transfer, with a minimum mixing speed of 400 RPM recommended to achieve efficient conversion [5]. The concentration of the catalyst significantly affects reaction performance.

While an optimal catalyst dose enhances biodiesel production, excessive catalyst loading can cause engine problems when using the fuel. Additionally, the type of catalyst used plays a crucial role in determining the quality of the final biodiesel product [5]. Another critical factor affecting biodiesel formation is the molar ratio of methanol to oil. 3:1 is the minimum required stoichiometric ratio for transesterification, which means that to produce three moles of fatty acid methyl esters (FAME), three moles of alcohol need to react with one mole of oil. The reaction equilibrium shifts forward when the methanol to oil ratio increases, improving biodiesel yield [5].

Types of catalysts that are being used in biodiesel production to accelerate the transesterification reaction are three, which are: acids, alkalis, and enzymes. Acid and alkali catalysts are further classified into homogeneous and heterogeneous catalysts, with these two types being more commonly used than enzyme-based catalysts [7]. Recent advancements in catalyst development have introduced promising alternatives, such as waste-derived heterogeneous catalysts that are both environmentally friendly and cost-effective for biodiesel production [8].

As biodiesel production increases as an alternative to fossil diesel, the amount of glycerol generated as a by-product also rises. Glycerol is the primary component of triglycerides and constitutes approximately 10% of biodiesel by weight. However, the large-scale production of glycerol presents an environmental challenge, as it cannot be simply discarded as waste. To be commercially viable, it must be separated from biodiesel and undergo further purification. The price of high-purity glycerol ranges between $1,200 and $1,800 per ton, making it neither excessively expensive nor costless [9]. (BOF) which refers to basic oxygen furnace slag is a significant by-product in the process of steelmaking, generated during the oxygen converter stage. This waste material contains free lime and free magnesia and accounts for approximately 15% to 20% of the total crude steel production [10]. BOF slag constitutes around 50% of the total steel slag produced and is widely recycled for various applications.

Due to the large quantities generated, BOF slag poses environmental challenges, making proper waste management essential for sustainable steel production. Since steel is a crucial component of the global economy, effective handling of this by-product is necessary to ensure continued production while minimizing environmental impacts.

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For many years, industrialized countries have utilized BOF slag as a landfill material and road ballast [11]. Additionally, it has been incorporated into cement production, offering benefits such as reduced energy costs and lower raw material consumption. Other applications include its use in hydraulic engineering projects and as a fertilizer. Furthermore, BOF slag can be processed into a hydraulic binder [12]. When it comes to a catalyst to be used to enhance the esterification reaction between waste cooking oil and alcohols in the process of biodiesel production, the BOF would be a good choice.

II. EXPERIMENTAL

A. Raw Materials

Three different raw materials were used in this work:

a) BOF slag resulted from steelmaking supplied from Egyptian Steel Factory at Ain El- Sokhna.

b) Sunflower waste cooking oil.

c) Methanol of 99% purity purchased from Morgan Chemical Ltd., Egypt.

B. Equipment and tools

- Sensitive balance (Sartorius AG Entris II, Germany).
- Hot plate magnetic stirrer (MSH-20D, Wisestir Ltd, Germany).
- Drying oven (Thermo Scientific Heratherm, US).
- Condensers, 100 ml, and 250 ml beakers.
- 250 ml tow necks Round bottom flask.
- 250 ml Separating funnels.
- Funnels, filter papers, pipettes, hoses, and parafilm.

C. Assessment of Raw Materials

1. *Chemical analysis (XRF)*

X-ray fluorescence spectrometry (XRFS) is a non-destructive elemental analysis technique used to identify and quantify the elements present in a sample. It measures the secondary emitted X-rays from the sample when exposed to a primary X-ray source. XRFS is commonly used with waste materials to determine its composition, providing insight into the concentrations of various oxides present. The analysis follows ASTM guidelines (C114-18) (ASTM C114-15, 2018).

2. *Mineralogical analysis (XRD)*

X-ray diffraction (XRD) identifies the sample crystalline phases present in it, whereas the elemental composition is determined by the X-ray fluorescence (XRF). The phase analysis is conducted using a PANalytical computer-certified program and the International Center for Diffraction Data (ICDD) database. In this analysis, a continuous scan was performed using a copper anode. The instrument default settings were set to 40 kV and 30 mA.

3. *Particle Size Distribution (PSD) Using Screen Analysis*

The particle size of the sample is determined using a set of sieves with standardized openings, measuring particle sizes from 0.0015 to 3 inches. The methodology follows ASTM D422-07 for particle size analysis and ASTM E11-09 for sieve specifications.

D. Biodiesel Production

1. *Experimental Procedure*

The transesterification reaction was carried inside a two neck 250 ml round-bottom flask with one neck connected to a condenser and the built-in thermometer penetrates the other neck. The experimental procedure was as follows:

- Oil Preparation: Sunflower waste cooking oil was collected from a home kitchen, filtered, and centrifuged to remove food residues and suspended particles.
- Water Removal: The oil was heated to 105°C for several hours to evaporate any residual water.
- Sample Preparation: Methanol and solid waste (acting as a catalyst) were added to the oil in the round-bottom flask.
- Stirring and Heating: A magnetic stirrer with a heating feature (Model: MSH-20D, Wisestir Ltd, Germany) was used to maintain the desired reaction temperature and agitation speed. A magnetic stir bar was placed in the flask to ensure proper mixing.
- Condensation: A reflux condenser was connected to a water source on one end and to the flask on the other, preventing methanol vaporization during heating.
- Reaction Variables: The experiment examined the effects of molar ratio between methanol and oil, catalyst loading, temperature of the reaction, and the time of the reaction. A total of 25 runs were conducted to determine the optimal conditions for maximum biodiesel yield.

The setup of the experiment that was used in the laboratory is illustrated in the figure below. The reaction time starts when the mixture reaches the desired temperature for each run. Temperature was continuously monitored and controlled automatically using the built-in thermometer attached to the hot plate magnetic stirrer.

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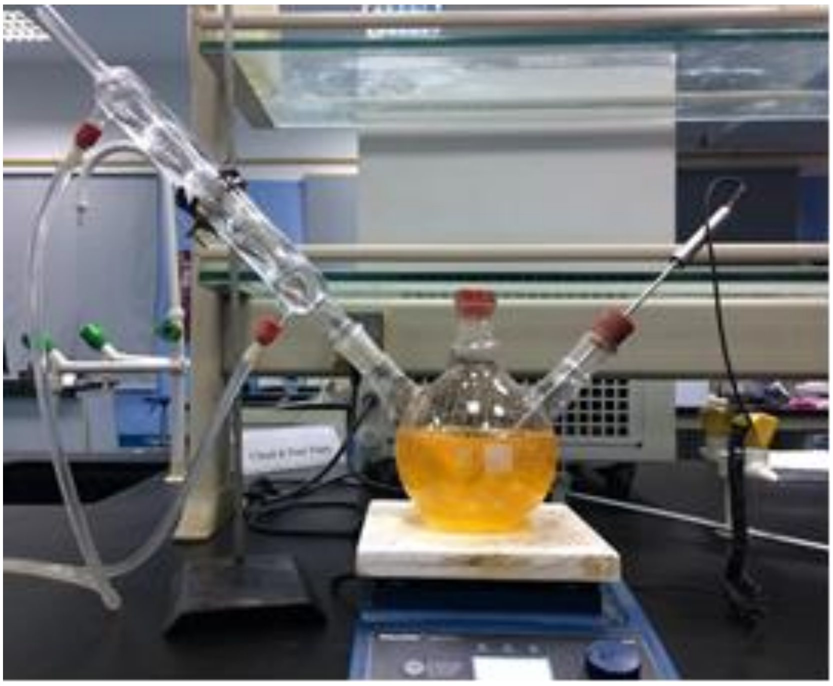

Figure 2: Experimental Setup

Once the required reaction time for the run had ended, the reaction was quenched by adding a few drops of methanol. The mixture was then filtered to remove the solid catalyst using filter paper placed over a conical flask. The resulting liquid was transferred to a separating funnel to allow for phase separation, as shown in the below figure.

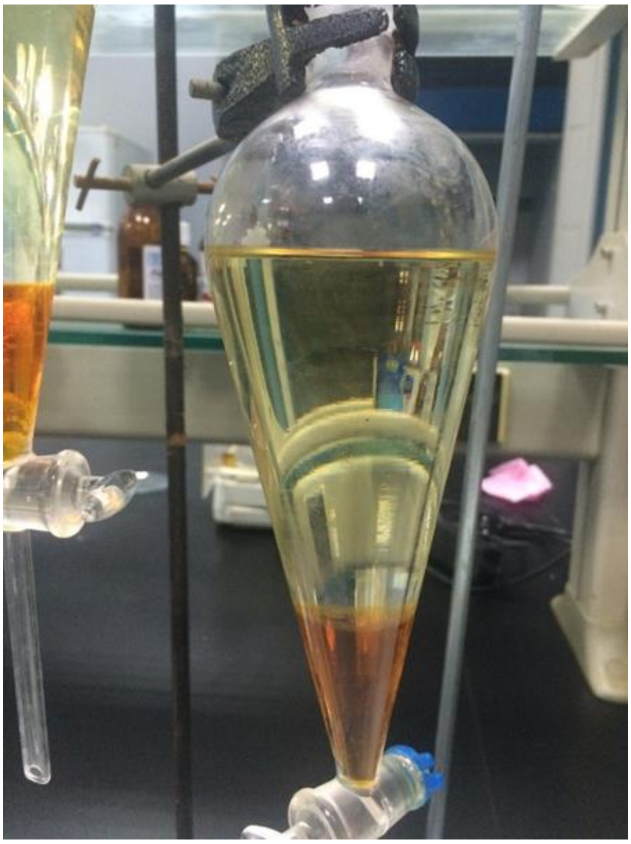

Figure 3: Products separation by settling process

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Two distinct immiscible layers formed due to differences in density. In most cases, glycerol is denser than biodiesel which as a result is settled at the bottom, on the other hand, biodiesel remained at the top. However, in some experimental runs, the biodiesel layer appeared at the bottom while the glycerol was on top. The biodiesel produced was then heated to 80°C for about half an hour to recover any unreacted amount of methanol by simple distillation.

The pure biodiesel weight was recorded, and the conversion was obtained by the following equation:

$$\textit{Converted Biodiesel } \% = \frac{\textit{Wt. of produced biodiesel}}{\textit{Wt. of waste oil used}} x100$$

2. *Experimental design*

The experimental work was designed using the Response Surface Methodology (RSM) technique, and a detailed process analysis was conducted using Design-Expert version 13. The primary reaction response was biodiesel conversion, while glycerol formation was also considered.

The key reaction variables were:

- Time of the reaction (A)
- Molar ratio of Methanol to oil (B)
- Percentage of Catalyst loading (C)
- Temperature of the reaction (D)
- Stirring rate of the reaction (E)

Table 1: FACTORS AFFECTING BIODIESEL PRODUCTION THROUGH TRANS-ESTRIFICATION REACTION

Factor	Unit	Label	Ranges	
			Minimum	Maximum
Time of reaction	Hours	A	1	4
Methanol to oil	Molarity ratio	B	5	20
Loading of catalyst	Wt. percentage	C	1	5
Temperature of reaction	Degrees Celsius	D	50	70
Rate of stirring	RPM	E	750	

The 25 experimental runs were incorporated into an uncertainty matrix to minimize the number of required experiments while ensuring statistical reliability. The runs were conducted in a randomized order, and the response values were calculated for each experiment based on the obtained results.

To design the experimental procedure, Design-Expert 13 software was used. The variables in the experiment and their corresponding values are presented in the table below.

Table 2: RUN MATRIX USED FOR PRODUCTION OF BIODIESEL EXPERIMENT

Run No.	Factor A	Factor B	Factor C	Factor D
1	1	5	1	50
2	4	5	1	50
3	1	20	1	50
4	4	20	1	50
5	1	5	5	50
6	4	5	5	50
7	1	20	5	50
8	4	20	5	50
9	1	5	1	70
10	4	5	1	70

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11	1	20	1	70
12	4	20	1	70
13	1	5	5	70
14	4	5	5	70
15	1	20	5	70
16	4	20	5	70
17	0.5	12.5	3	60
18	5.5	12.5	3	60
19	2.5	2.5	3	60
20	2.5	27.5	3	60
21	2.5	12.5	1	60
22	2.5	12.5	7	60
23	2.5	12.5	3	40
24	2.5	12.5	3	80
25	2.5	12.5	3	60

The reaction variables were optimized based on specific targets, considering both economic and environmental factors. The primary goal was to minimize biodiesel production costs by utilizing milder reaction conditions while maintaining high yield and quality. Achieving maximum biodiesel yield at lower temperatures and shorter reaction times helps reduce energy consumption, save time, and increase profitability.

The experimental design, regression analysis, graphical analysis, and the numerical optimization were conducted by the use of the Design-Expert version 13 software.

III. RESULTS AND DISCUSSION

A. Analysis of BOFS

1. *Chemical Analysis*

The XRF analysis of BOF slag is presented in the below Table, showing that this waste primarily consists of CaO, along with other oxides. Previous research has demonstrated that metal oxides serve as effective catalyst in biodiesel production. Given its composition, BOF slag holds strong potential as a catalyst for biodiesel synthesis.

Table 3: CHEMICAL ANALYSIS FOR BOF SLAG

Oxides	%
Fe_2O_3	10.9
FeO	10.7
ZnO	2.3
CaO	45
SiO_2	11.1
Al_2O_3	1.9
MnO	3.1
MgO	9.6

2. *Mineralogical Analysis of BOF slag*

The mineralogical analysis of the ground BOF slag revealed that it primarily consists of periclase (MgO), zincite (ZnO), manganese oxide (MnO), alite (Ca_3SiO_5), and xifengite (Fe_5Si_3)**.** These mineral phases contribute to the material's potential catalytic properties for biodiesel production.

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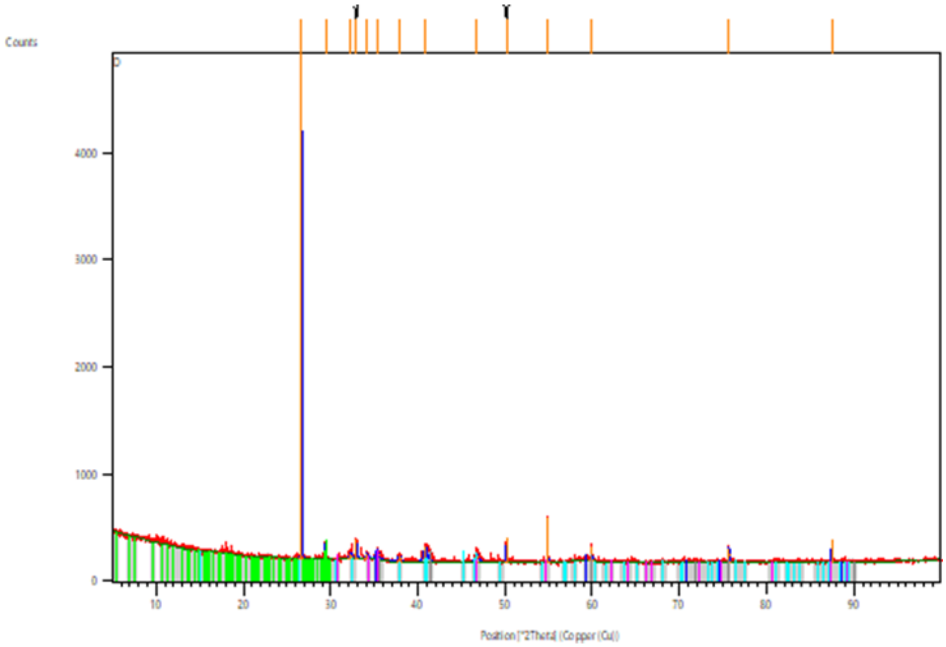

Figure 4: Mineralogical analysis of BOF slag

3. Screen Analysis of BOF slag

The below Figure illustrates distribution of BOF slag particle size, showing that the powder consists of very fine particles with an average size of 537 nm. Smaller particle sizes are advantageous for catalytic applications, as they result in a larger surface area and a greater number of active sites available for the reaction. This enhanced surface activity improves catalyst efficiency, ultimately leading to a higher biodiesel yield.

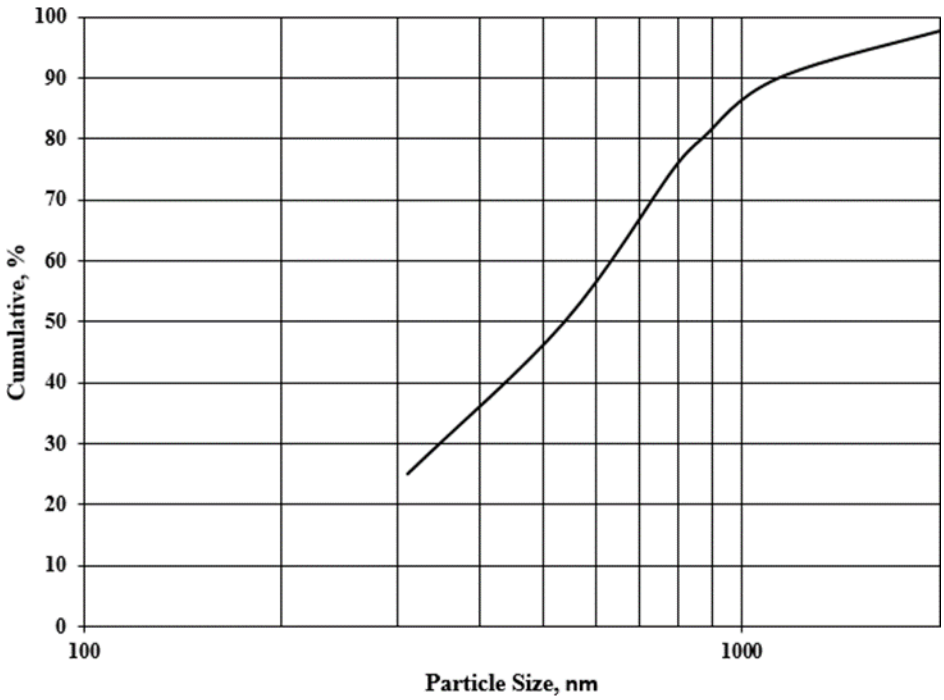

Figure 5: BOF slag Particle size distribution

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B. Analysis on the chemical reaction

1. *Adequacy checking and model fitting*

The generated equation of regression from the software of the Design-Expert which represents the empirical relation between the yield of produced biodiesel (Y) and the reaction parameters is shown below:

$$Y=69.092+0.09A+1.018B+0.059C+0.213D-0.309AB+0.884AC+0.007AD-0.079BC-0.009BD-0.001CD+0.005ABD-0.013ACD+0.0014BCDY = 69.092 + 0.09A + 1.018B + 0.059C + 0.213D - 0.309AB + 0.884AC + 0.007AD - 0.079BC - 0.009BD - 0.001CD + 0.005ABD - 0.013ACD + 0.0014BCDY=69.092+0.09A+1.018B+0.059C+0.213D-0.309AB+0.884AC+0.007AD-0.079BC-0.009BD-0.001CD+0.005ABD-0.013ACD+0.0014BCD$$

Where:

- Biodiesel yield response is represented by the symbol Y.
- Time (hrs) of the reaction was represented by the symbol A.
- Methanol to oil molar ratio was represented by the symbol B.
- Catalyst wt. loading (%) was represented by the symbol C.
- The temperature (°C) of the reaction was represented by the symbol D.

To evaluate the statistical significance of the model, Analysis of Variance (ANOVA) was applied at a 95% confidence level. The significance of each parameter was determined using p-values and the F-test:

- A high F-test value (75.06) and a low p-value (0.0132) indicate a strong statistical significance of the model.
- The model's reliability was further validated using coefficient values:

  - Adjusted R^2 (R^2adj) = 0.9847
  - R^2 = 0.9980

These values confirm that 98.8% of the variance is attributed to the model, demonstrating its high predictive accuracy. Additionally, a graph of predicted vs. actual biodiesel yield was plotted to illustrate the strong correlation between experimental and predicted values. The close agreement between actual and estimated results highlights the model's effectiveness in predicting biodiesel yield with high accuracy.

Table 4: ANOVA FOR REDUCED QUADRATIC MODEL RESPONSE 1 (BIODIESEL YIELD)

Source	**Sum of Squares**	**Mean Square**	**F-value**	**p-value**	
Model	9648.65	507.82	84.56	< 0.0001	significant
A-Reaction Time	34.22	34.22	5.70	0.0382	
B-Methanol/oil ratio	590.09	590.09	98.26	< 0.0001	
C-Catalyst loading	66.00	66.00	10.99	0.0078	
D-Temperature	0.0449	0.0449	0.0075	0.009328	
AB	34.02	34.02	5.67	0.0386	
AC	5.31	5.31	0.8842	0.03692	
AD	40.11	40.11	6.68	0.0272	
BC	0.0762	0.0762	0.0127	0.009125	
BD	114.89	114.89	19.13	0.0014	
CD	1.50	1.50	0.2494	0.006283	
B^2	20.97	20.97	3.49	0.0912	
D^2	815.37	815.37	135.77	< 0.0001	

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Table 5: ANOVA FOR REDUCED QUADRATIC MODEL RESPONSE 2 (GLYCEROL YIELD)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	11453.21	8	1431.65	387.53	< 0.0001	significant
A-Reaction Time	430.00	1	430.00	116.40	< 0.0001	
B-Methanol/oil ratio	3899.62	1	3899.62	1055.58	< 0.0001	
C-Catalyst loading	4.58	1	4.58	1.24	0.2780	
D-Temperature	6708.60	1	6708.60	1815.94	< 0.0001	
AD	25.35	1	25.35	6.86	0.0160	
BD	144.36	1	144.36	39.08	< 0.0001	
B^2	28.13	1	28.13	7.62	0.0117	
D^2	91.28	1	91.28	24.71	< 0.0001	

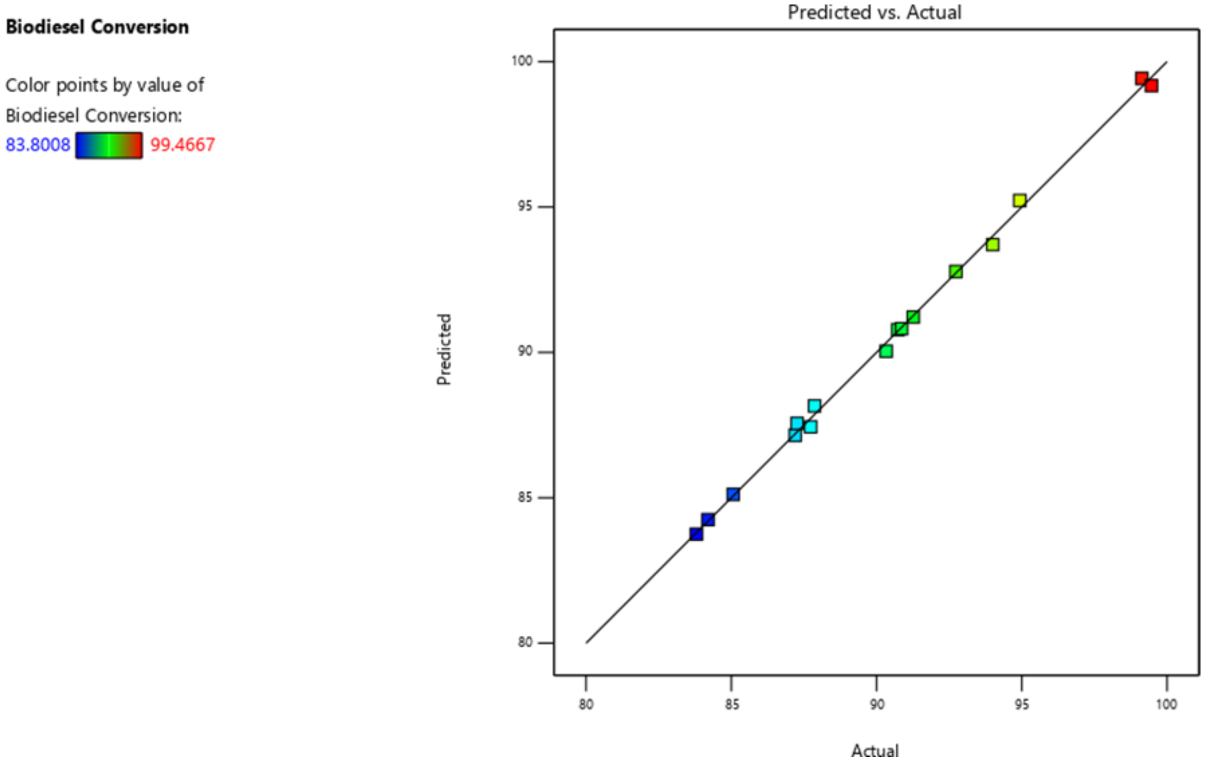

Figure 6: Predicted values versus experimental actual data of biodiesel yield in percentage

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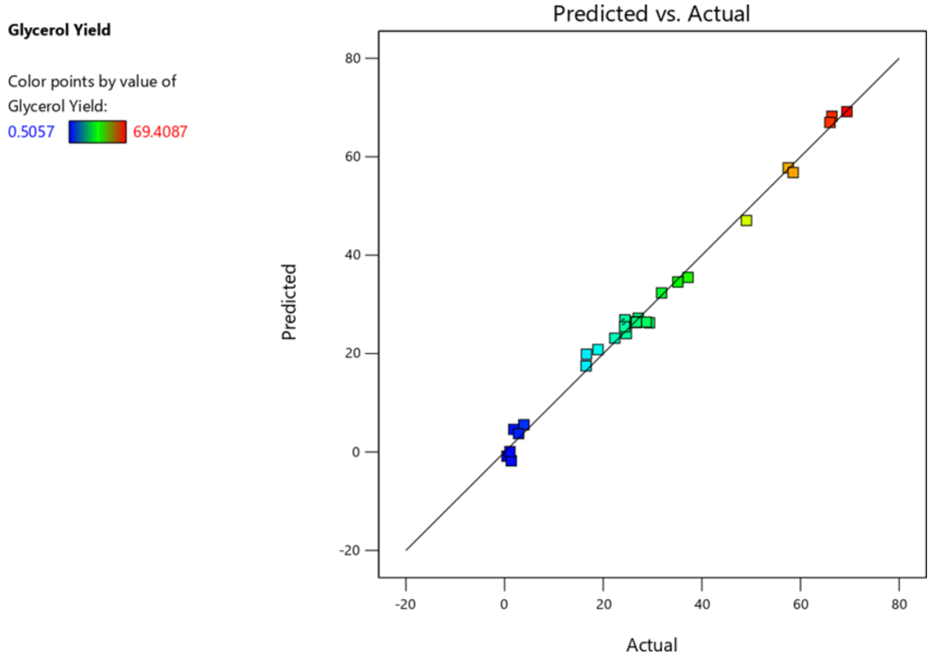

Figure 7: Predicted values versus experimental actual data of glycerol yield in percentage

2. *Effect of process variables*

- *Methanol to oil (M:O) molar ratio*

The molar ratio between methanol and oil is a crucial variable in the production of biodiesel. Regarding the stoichiometry of the transesterification reaction, three moles of biodiesel could be produced when three moles of methanol react with a mole of oil. Increasing the methanol concentration helps the reaction to drive forward, promoting the formation of biodiesel and sustaining the reaction rate.

To study the effect of excess methanol, the molar ratio between methanol and oil was set between 5:1 to 20:1. This range was selected to determine the effect of excess methanol on the yield of biodiesel produced and to identify the optimum ratio for maximum efficiency.

As illustrated in the figure below, biodiesel yield significantly increases with higher molar ratios of methanol to oil, demonstrating the positive influence of methanol excess on the reaction's conversion efficiency.

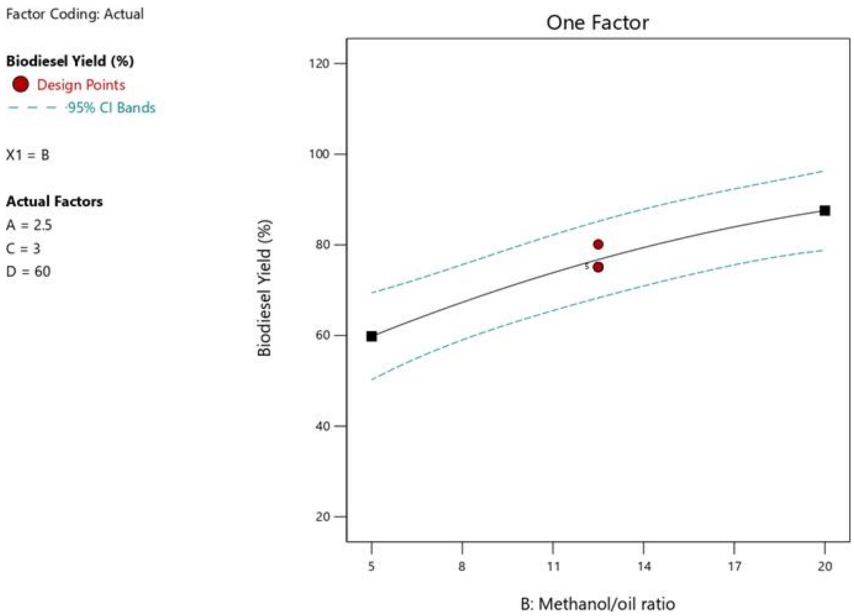

Figure 8: Effect of M:O molar ratio on biodiesel yield

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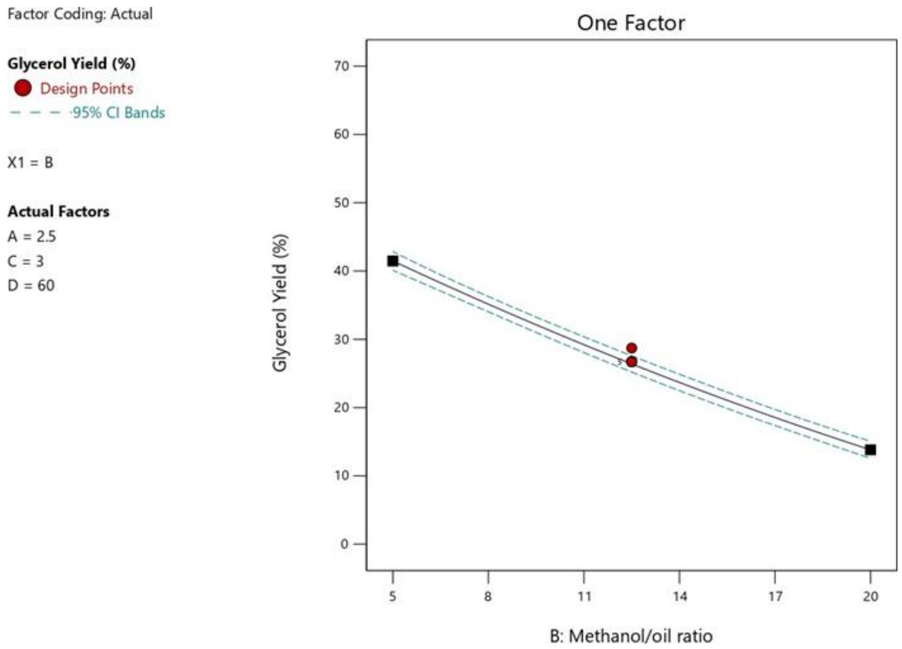

Figure 9: Effect of M:O molar ratio on glycerol yield

- *The solid waste (BOFS) weight percentage*

The amount of BOF slag used is a key variable in biodiesel production, as it functions as a heterogeneous catalyst that accelerates the oil conversion to biodiesel. Increasing the catalyst loading enhances the active sites available number, thereby improving the reaction rate due to greater surface interaction between reactants and catalyst particles. To evaluate this effect, the catalyst load was varied within a range of 1% to 5% by weight. This range was selected to study the influence of BOF slag quantity on the biodiesel yield.

As illustrated in the figure below, biodiesel yield shows a gradual increase with higher catalyst loading, indicating that more catalyst contributes to improved conversion, although the enhancement becomes less significant at higher percentages.

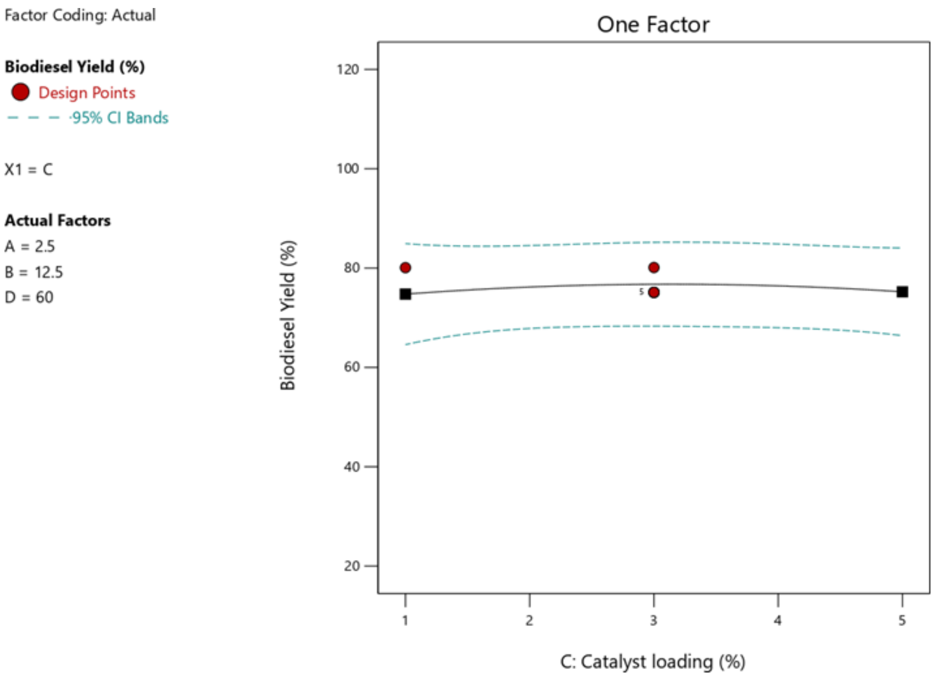

Figure 10: Effect of catalyst loading percentage on biodiesel yield

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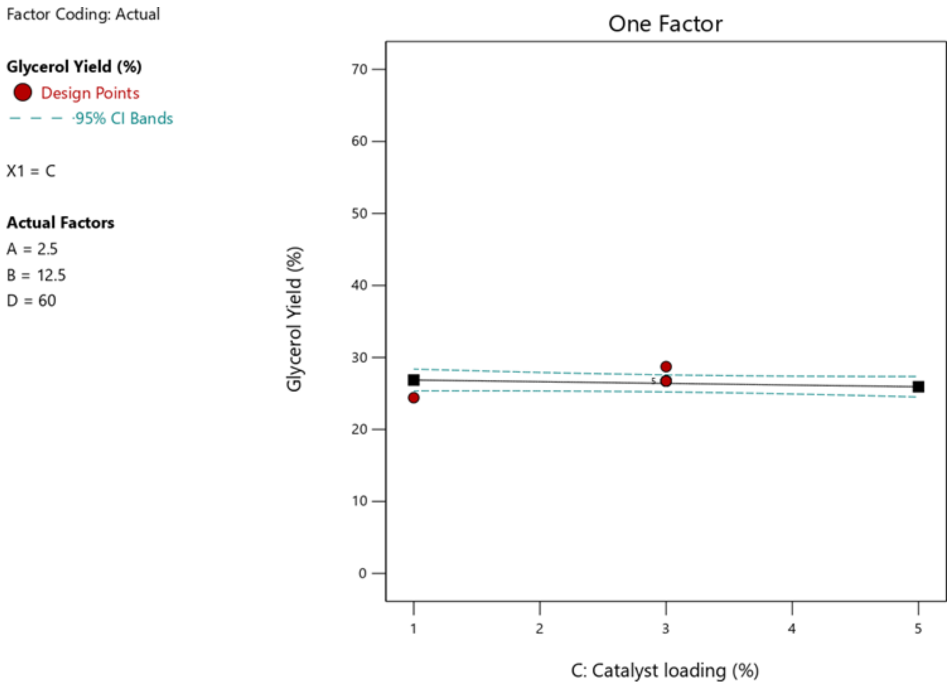

Figure 11: Effect of catalyst loading percentage on glycerol yield

- *The reaction temperature*

Reaction temperature is a critical factor influencing the efficiency of biodiesel production. It directly affects the reaction rate, viscosity of the oil, and the solubility of methanol in the reaction mixture. To investigate its effect, a range of temperatures from 55°C to 75°C were selected for the transesterification reaction.

As shown in the figure below, the biodiesel yield increases with rising temperature, which is attributed to enhanced molecular interaction and improved mass transfer at elevated temperatures. However, it is essential not to exceed the methanol boiling point or degrade sensitive compounds in the reaction.

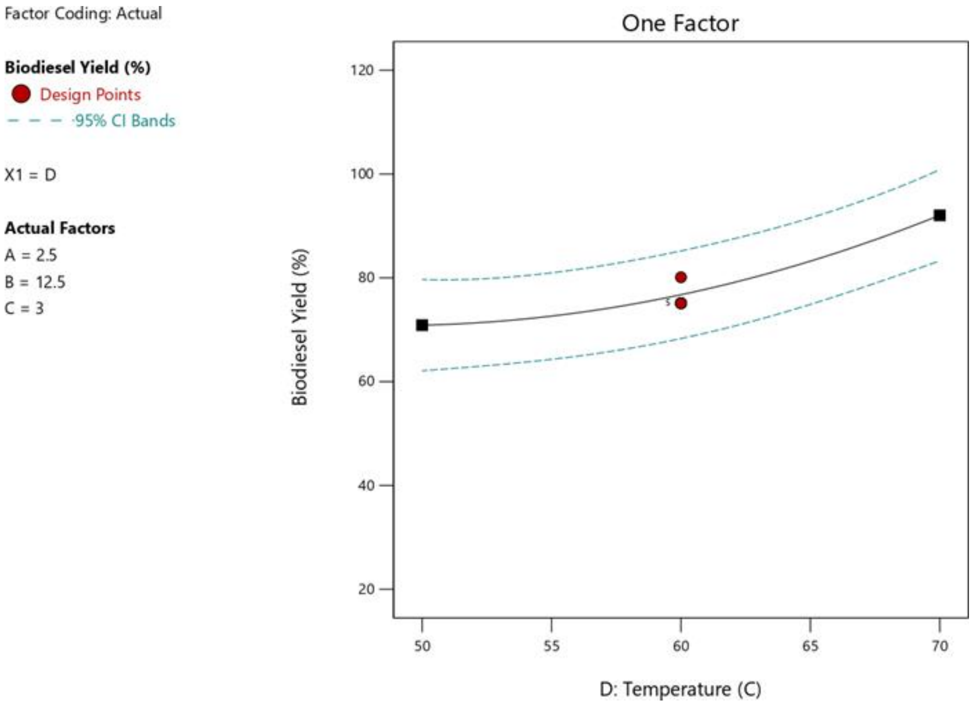

Figure 12: Temperature of the reaction effect on the yield of produced biodiesel

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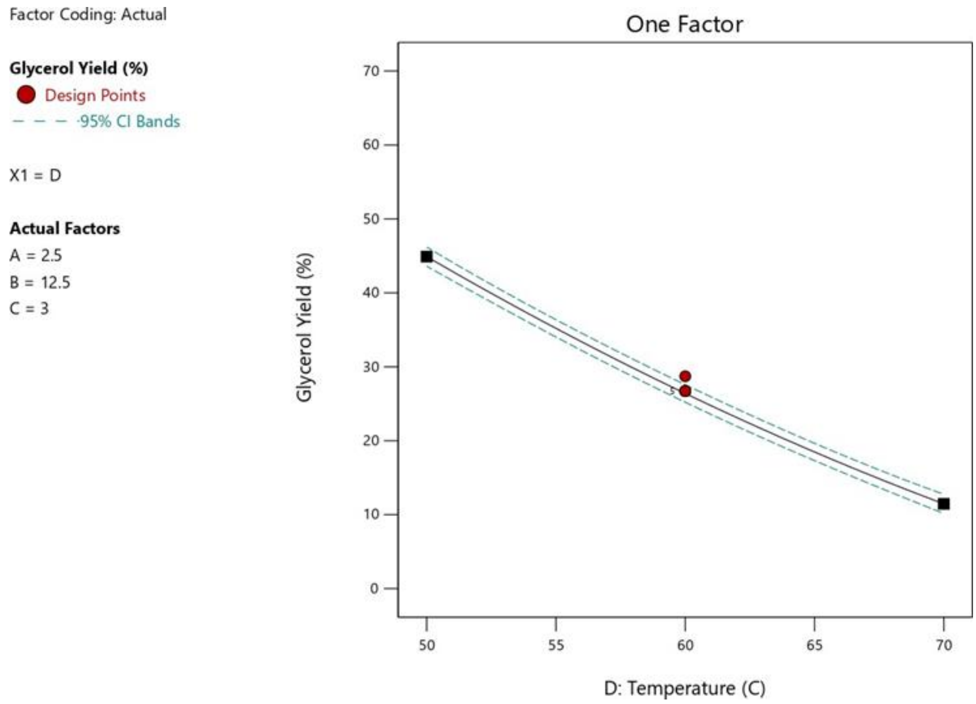

Figure 13: Temperature of the reaction effect on the yield of produced glycerol

- *The reaction time*

The time of the reaction is a key variable in the production of biodiesel, as it influences the extent of oil conversion to biodiesel. Generally, increasing the time of the reaction allows the reaction to proceed more completely, resulting in a higher yield. However, this increase is not continuous, as the yield tends to plateau after reaching an optimal duration, beyond which further time does not significantly enhance conversion and may lead to side reactions or energy waste.

To evaluate its effect, the time of the reaction was varied from 1 hour to 4 hours. This range was selected to determine the optimal reaction duration that ensures maximum biodiesel yield without unnecessary extension of process time.

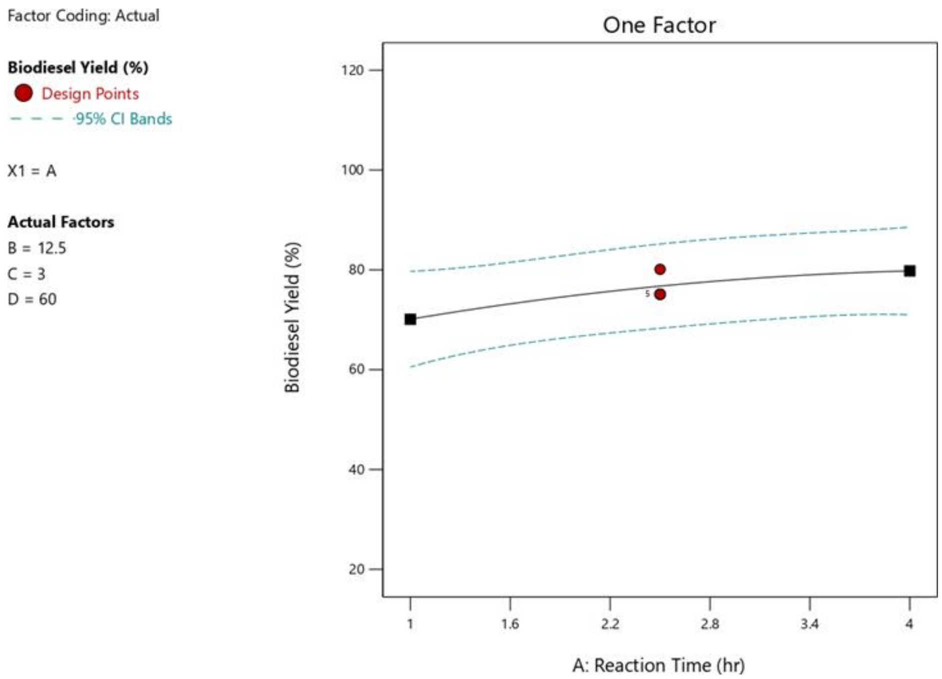

Figure 14: Effect of reaction time on biodiesel yield

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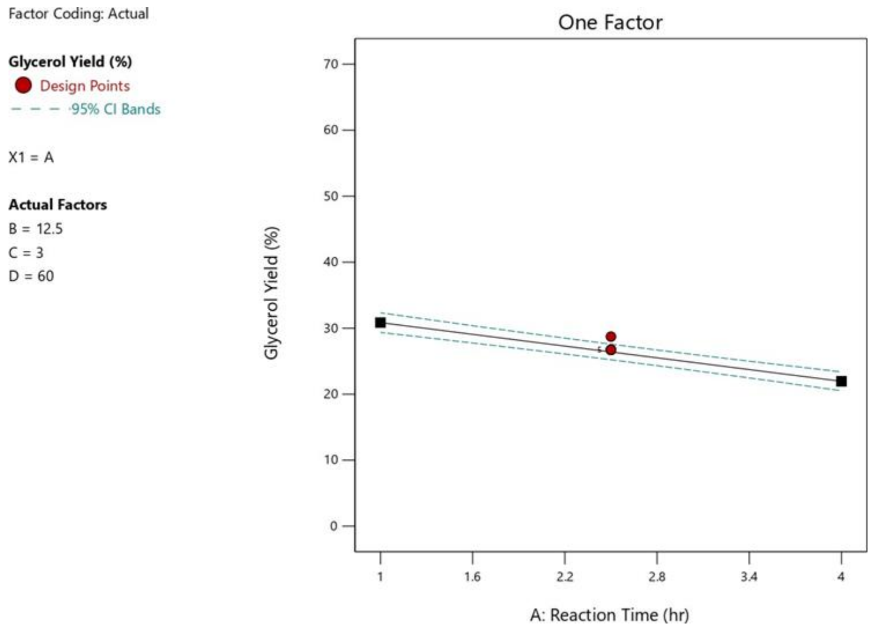

Figure 15: Effect of reaction time on glycerol

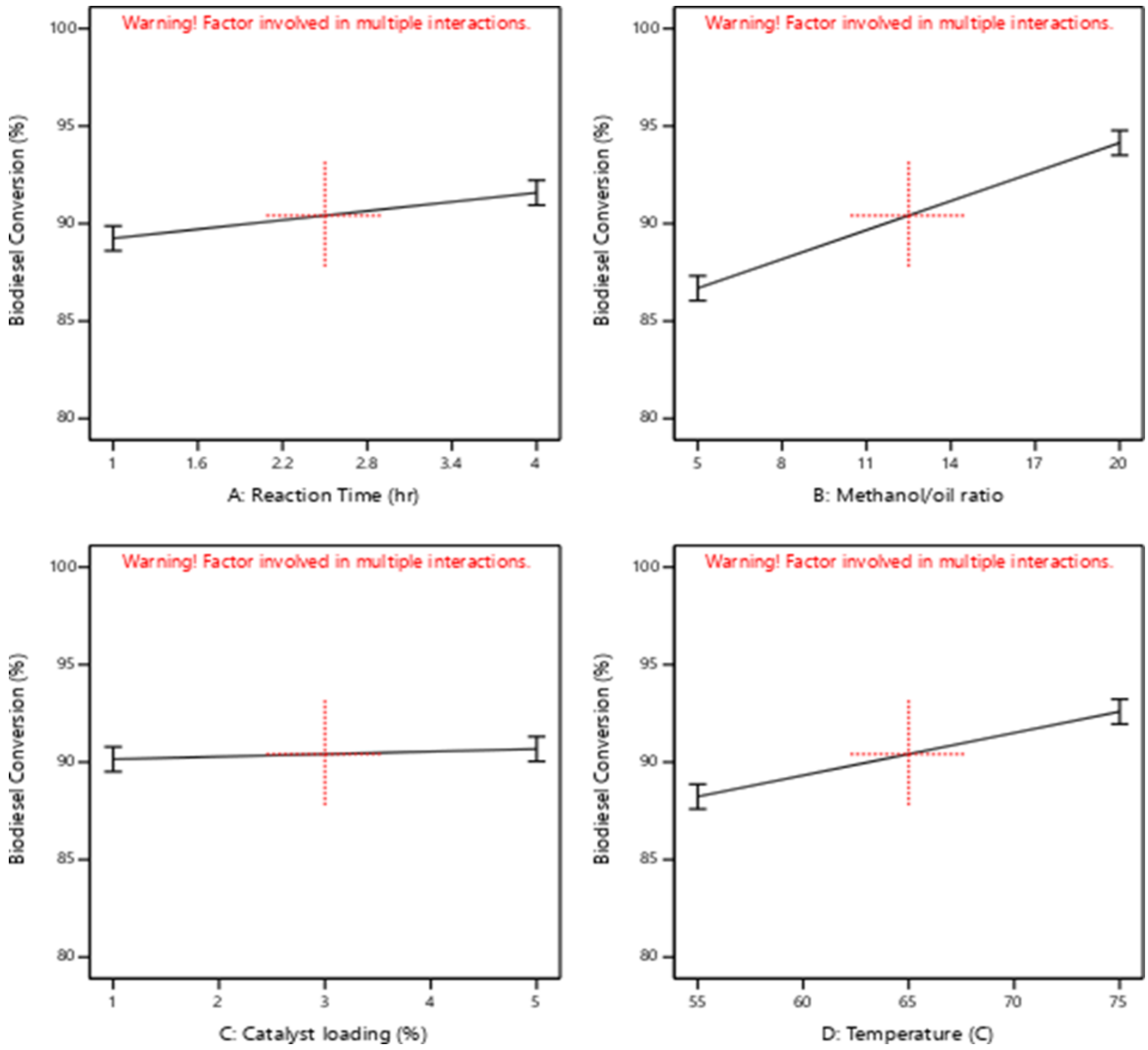

Figure 16: Effect of all reaction parameters on biodiesel yield

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3. *Interactions of process variables effect*

The below surface plots illustrate the combination between the effects of the reaction variables -molar methanol to oil ratio**,** reaction temperature (°C)**,** reaction time (hours), and catalyst loading (wt.%)- on the yield of biodiesel. These plots visually represent how variations in each parameter influence the conversion efficiency, identifying the optimum conditions to produce maximum yield of biodiesel.

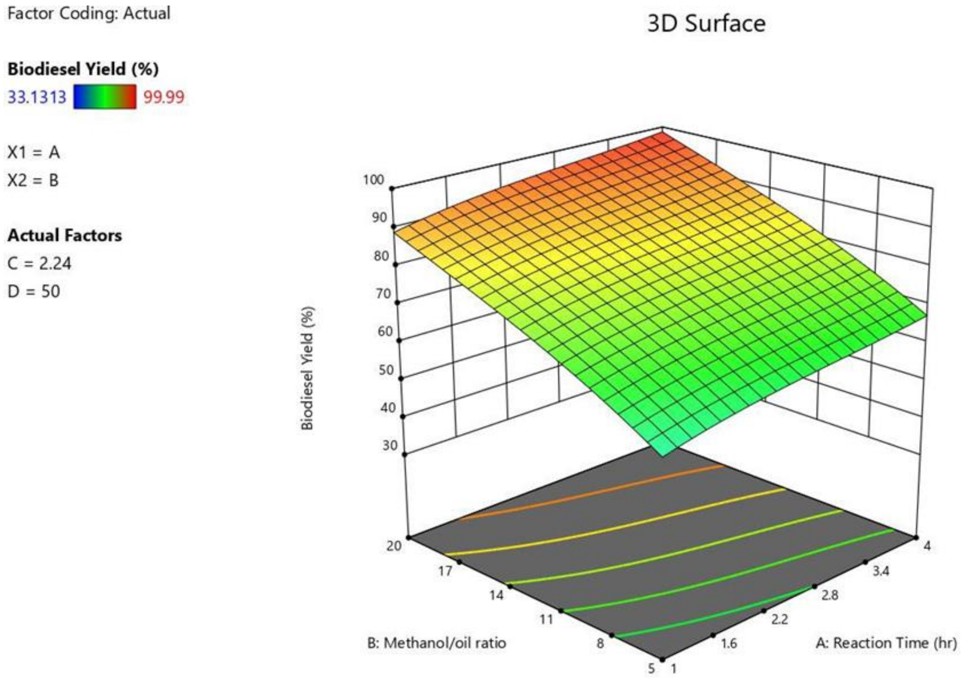

Figure 17: Effect of methanol to oil molar ratio and reaction time on biodiesel yield

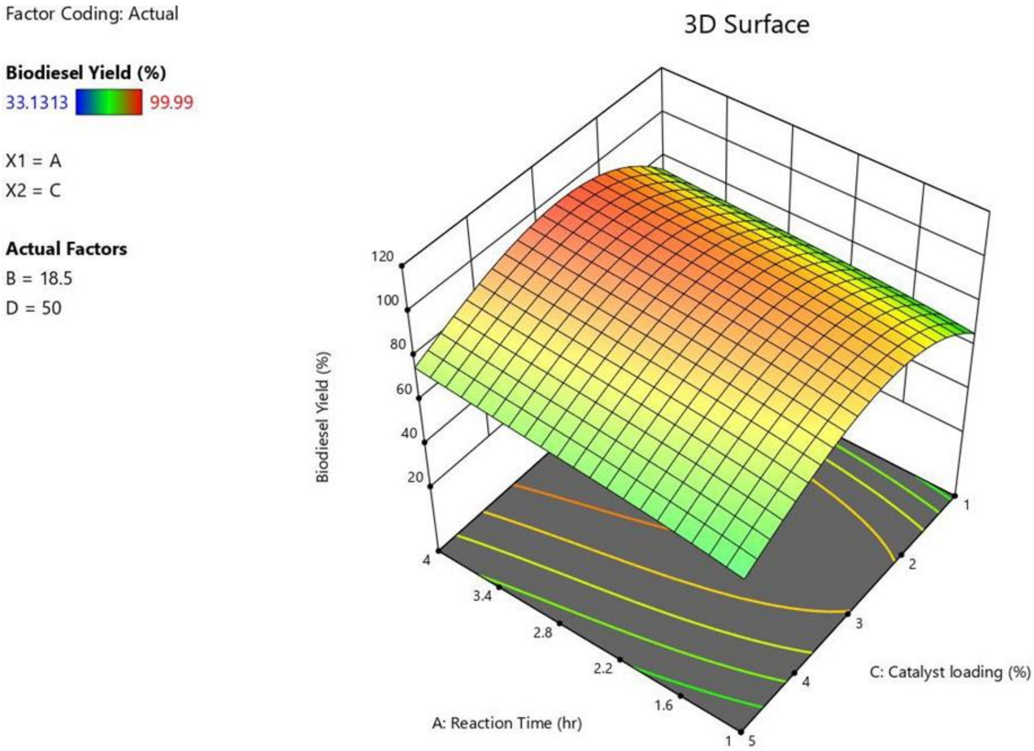

Figure 18: Effect of catalyst loading percentage and reaction time on biodiesel yield

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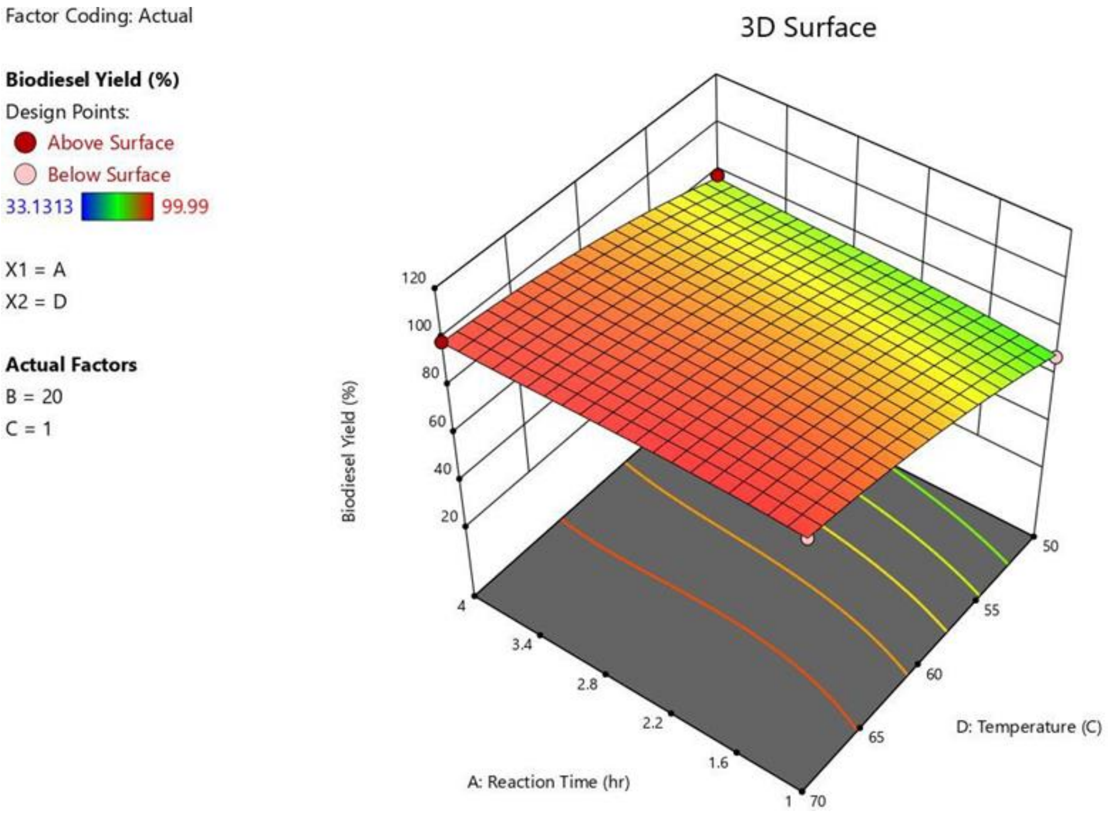

Figure 19: Temperature of reaction and time of reaction effect on yield of produced biodiesel

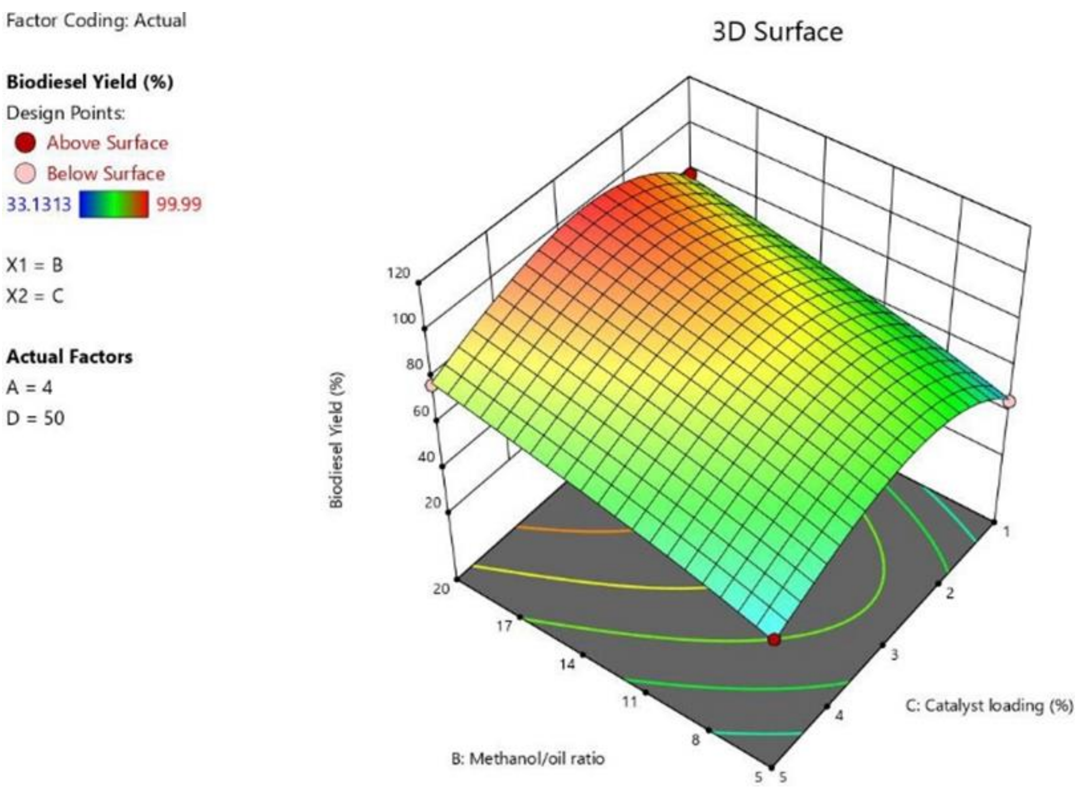

Figure 20: Effect of catalyst loading percentage and methanol to oil molar ratio on biodiesel yield

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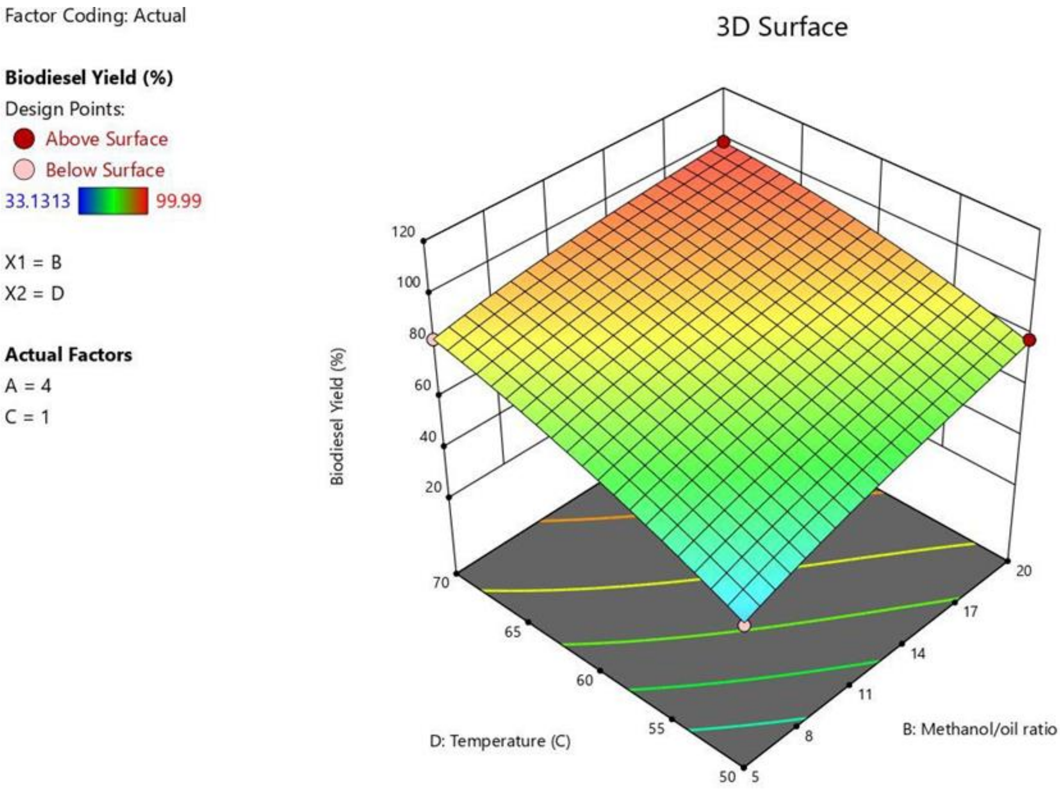

Figure 21: Effect of reaction temperature and methanol to oil molar ratio on biodiesel yield

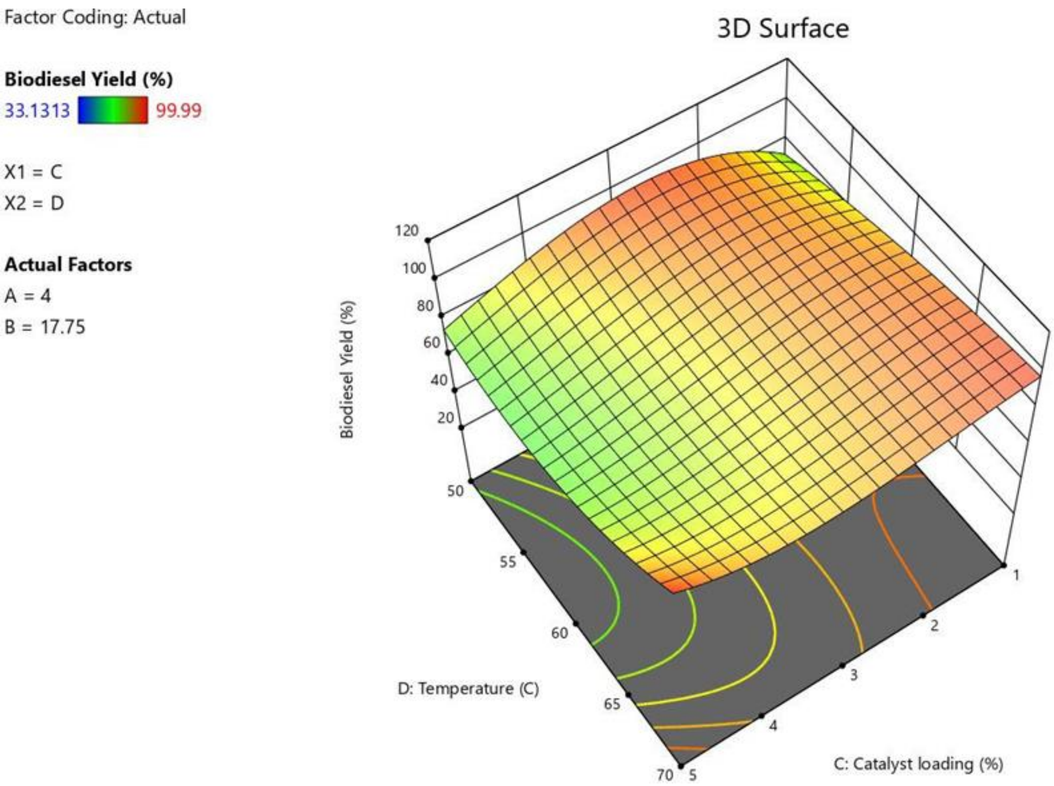

Figure 22: effect of reaction temperature and catalyst loading percentage on biodiesel yield

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C. Optimization of reaction variables

The transesterification reaction optimization for biodiesel production was conducted using Design-Expert® software, focusing on identifying the optimum values of the independent variables of the reaction -reaction time, temperature, catalyst loading, and molar methanol to oil ratio- that influence the dependent response variable to enhance the yield of biodiesel.

To guide the optimization process, specific goals were defined within the software, aiming to balance economic and environmental considerations. Variables associated with high energy consumption, such as reaction time and temperature, were assigned the highest level of importance (fifth degree) for reduction. The molar methanol to oil ratio was also set to be minimized but given a lower importance (first degree), since excess amount of methanol can be recovered and reused. The biodiesel yield, as the response variable, was set to be maximized to ensure the highest possible conversion efficiency under the optimum conditions.

Through numerical optimization, the software generated 83 potential solutions that met the defined criteria. The highest desirability solution (74.2%) was selected. The optimum conditions identified were:

- Methanol to oil ratio: 20:1
- Reaction temperature: 57 °C
- Catalyst loading: 5 wt.%
- Reaction time: 1 hour
- Stirring rate: 750 rpm

These conditions yielded a maximum biodiesel conversion of 90.163%, demonstrating the effectiveness of the optimization strategy.

D. Analysis on optimum sample of Biodiesel yield produced

***1.** Sample of optimum yield Biodiesel produced physicochemical properties*

The biodiesel sample produced under the optimized reaction conditions was analyzed to determine its physicochemical properties, including calorific value, density, kinematic viscosity, flash point, pour point, and cloud point. These parameters are critical for evaluating the fuel quality and its suitability as a diesel alternative.

To assess its compliance and performance, the measured properties of the produced biodiesel were compared with the Biodiesel International Standard EN 14214 and the American Standard ASTM D6751, as summarized in the table below.

Table 6: PRODUCED BIODIESEL PHYSICOCHEMICAL PROPERITIES

Test name	Method used	Biodiesel produced	ASTM D6751	(EN14214)
Calorific value (MJ/kg)	ASTM D-5865	40.181665		> 32.9
Density at 15^{o}C (g/cm^{3})	ASTM D-4052	0.8851		0.86 – 0.9
Kinematic viscosity at 40^{o}C (cSt)	ASTM D-445	4.8	1.9 – 6.0	3.5 – 5.0
Flash point (^{o}C)	ASTM D-93	170	> 130	> 101
Pour point (^{o}C)	ASTM D-97	-22		
Cloud point (^{o}C)	ASTM D-97	-14		< -4

As shown in the table above, all the properties measured for the experimental biodiesel were found to be within the acceptable limits of both, the American Biodiesel Standard ASTM D6751 and Biodiesel International Standard EN 14214, confirming the successful production of high-quality biodiesel. These results strongly support the potential of BOF slag as an effective and sustainable heterogeneous catalyst in biodiesel production.

***2.** Gas Chromatography (GC) Analysis*

The optimum biodiesel sample, produced from the transesterification reaction between sunflower waste cooking oil and methanol using BOF slag as a catalyst, was further characterized through gas chromatography (GC). The total Fatty Acid Methyl Esters (FAME) content in the sample was determined using the EN 14103 standard method, while the total glycerol, free glycerol, and triglyceride contents were analysed according to the EN 14105 standard method.

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The results obtained from both EN 14103 and EN 14105 analysis are presented in the following table. These results confirm that the biodiesel sample complies with the required quality specifications, validating its suitability as a diesel substitute.

Table 7: GAS CHROMATOGRAPHY ANALYSIS RESULTS

Test	Results	Specifications		Units	Standard Methods
		Minimum	Maximum		
Total FAME	97.6	96.5		%. (m/m).	EN 14103
Free Glycerol	0.01		0.02	%. (m/m).	EN 14105
Total Glycerol	0.019		0.25	%. (m/m).	EN 14105
Monoglycerides	0.0043		0.80	%. (m/m).	EN 14105
Diglycerides	0.0078		0.20	%. (m/m).	EN 14105
Triglycerides	0.0856		0.20	%. (m/m).	EN 14105

IV. CONCLUSION

This project focuses on the utilization of Basic Oxygen Furnace (BOF) slag, which is produced from the steel-making industry as a by-product, as a heterogeneous base catalyst for biodiesel production through transesterification. This slag, typically considered a waste due to its massive annual production and environmental impact, was explored as a catalyst for converting used cooking oil -another problematic waste- into biodiesel. This approach not only addresses waste management concerns but also provides environmental and economic benefits by eliminating the need for fresh oil feedstocks.

Four key variables were examined to assess how they affect glycerol and biodiesel yields: temperature of the reaction, time of the reaction, molar methanol to oil ratio, and percentage of catalyst loading. The results demonstrated that increasing any of these variables generally led to a higher biodiesel yield. For instance, longer reaction times, higher temperatures, greater methanol-to-oil ratios, and increased catalyst amounts all positively influenced the biodiesel production efficiency, as confirmed by the figures in the result section.

The Design-Expert® software was employed for experimental design, model generation, statistical analysis, and optimization. A total of 25 experimental runs were performed, providing insight through predictive models, 2D graphs, 3D surfaces plots, and contour diagrams. The optimization process was guided by both environmental and economic considerations. The software generated 83 optimal solutions, with the highest desirability (74.2%) corresponding to the following optimal conditions:

- Reaction temperature: 57 °C
- Reaction time: 1 hour
- Methanol-to-oil ratio: 20:1
- Catalyst loading: 5 wt%
- Stirring rate: 750 rpm

Under these optimal conditions, the biodiesel yield achieved was 90.163%, and the final product met international biodiesel standards, validating the effectiveness of BOF slag as a sustainable catalyst in biodiesel production.

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