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Synthesis and characterization of biodiesel from mango kernel oil via transesterification using Response Surface Methodology (RSM)

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Abstract

Biodiesel production through transesterification is influenced by several operational factors, including feedstock type, catalyst concentration, methanol-to-oil ratio, reaction temperature, mixing intensity, and reaction time, which often limit its large-scale application. This study applied Central Composite Design (CCD) under Response Surface Methodology (RSM) to optimize these variables for biodiesel production from mango seed kernel oil. The oil was extracted and characterized using standard procedures, and transesterification was performed according to CCD-generated conditions. The highest biodiesel yield of 91.94% was achieved at a methanol-to-oil ratio of 9:1, catalyst loading of 3 wt%, temperature of 55°C, and reaction time of 60 min, demonstrating efficient conversion. Statistical analysis showed that all parameters significantly influenced yield ($p < 0.0001$). The strong agreement between experimental and predicted results, supported by high R^2 (0.9948), adjusted R^2(0.9900), and predicted R^2(0.9702) values, confirmed the model's reliability for yield prediction. Physicochemical analysis indicated that the oil is a suitable biodiesel feedstock; however, minimal pretreatment, such as drying or antioxidant addition, may improve its stability. The resulting biodiesel displayed promising properties but is best applied in blends with petroleum diesel or higher-quality biodiesel to enhance fuel performance.

Keywords: Mango seed oil, transesterification, biodiesel, RSM.

Introduction

Over the past decades, global energy needs have been met primarily through fossil fuels, particularly oil, natural gas, and coal[1-3]. Although these resources have supported industrial and economic growth, their overuse has created significant energy challenges worldwide[3]. Nigeria presents a clear example, despite being a leading producer of petroleum and natural gas, the country still struggles with frequent energy shortages due to its dependence on fossil resources[4]. Rapid population growth, urbanization, and industrialization further accelerate the depletion of these non-renewable reserves[1,4].

Moreover, the use of fossil fuels for energy generation results in considerable greenhouse gas emissions, mainly in the form of carbon dioxide, which intensifies global warming and climate change[3].To address these challenges, biofuels have been identified as a sustainable alternative because they are renewable, biodegradable, energy-rich, and environmentally friendly[3,5,6]. Projections by the International Energy Agency (IEA) and the United States Department of Energy suggest that replacing fossil fuels with biofuels could reduce global carbon dioxide emissions by up to 50% by 2050[6]. Examples include bioethanol (from corn and sugarcane), biodiesel (from edible-oils, non-edible oils, animal fats, algae, and biomass), and biogas (methane from organic waste and manure).

Biodiesel is widely recognized as a renewable and environmentally friendly fuel with strong potential to address the negative impacts of fossil fuel use. It is mainly composed of fatty acid methyl esters (FAME), which are produced from plant- and animal-based oils through sustainable conversion processes[7,8]. Transesterification is the most prevalent process for producing biodiesel. In this process, lipids such as vegetable oils, waste cooking oils, or animal fats react with short-chain alcohols, typically methanol or ethanol, in the presence of a catalyst, yielding biodiesel and glycerol as products[8].

Various catalyst types have been reported, including homogeneous (e.g., NaOH, KOH) and heterogeneous catalysts (e.g., CaO, MgO), biocatalysts, and nanocatalysts. Notably, nanocatalysts have emerged as highly effective alternatives because of their enhanced surface area, superior mass transfer, modifiable surface chemistry, and strong thermal stability, which together improve yield, reduce reaction time, and support catalyst reusability[9].

Moreover, several process variables, such as feedstock type, affect biodiesel production. Catalyst concentration, methanol-to-oil ratio, temperature, mixing, and reaction time[9]. The main industrial challenge is achieving high yields while meeting quality standards. Optimizing these factors lowers costs, improves fuel performance, and reduces emissions, making large-scale production more feasible[10].

RSM models are frequently employed nowadays for optimization applications since they can solve problems more quickly than other optimization strategies[12]. RSM combines statistical and mathematical techniques to establish relationships between independent variables and response outputs, allowing for process design, improvement, and optimization[13]. In addition, it helps to minimize experimental errors and improve accuracy through structured experimental designs. The choice of design, however, depends on the number of variables and levels under investigation[14]. The most commonly used are Central Composite Design (CCD) and Box-Behnken Design (BBD), each with specific strengths and limitations[15,16].

In this study, biodiesel production from mango seed kernel oil was optimized utilizing potassium hydroxide (KOH) as a catalyst within the RSM framework, employing CCD for experimental design.

Materials and Methods

Sample collection and preparation: The mango seed samples were collected from various dumping locations, where they were discarded as waste after eating the fruit pulp. They were cracked with a small hammer to obtain the kernels. To facilitate extraction, the kernels were air-dried in the laboratory for one week before being crushed into smaller particles with a grinding machine. The powdered sample was then oven-dried at 105°C for 2 h, cooled to room temperature, and stored in a plastic container until analysis.

Oil extraction: Oil extraction was carried out in a 500 ml Soxhlet apparatus using 250 ml of n-hexane as the solvent. A measured quantity (15 g) of the prepared sample was loaded into a porous extraction thimble and subjected to continuous solvent extraction with n-hexane at 65 °C for 6 h 17 min. To obtain sufficient oil for subsequent transesterification, the extraction procedure was repeated. The recovered oil was then transferred to a volumetric flask, vacuum-filtered to remove contaminants, and left alone for 48 h to allow suspended solids to settle. The solvent was then removed, and the oil was extracted using a rotary evaporator set to 50 degrees Celsius. Equation-1 was used to calculate the % oil yield.

$$\text{Oil yield (\%)} = \frac{W_2 - W_0}{W_1} \text{ x } 100 \quad (1)$$

Where: W_1 = weight of sample (g), W_2 = weight of flask + oil (g) and W_0 = weight of flask (g), Physicochemical characterization of the oil

The extracted mango seed oil was further characterized to determine its physicochemical properties, including density, moisture content, kinematic viscosity, saponification value, acid value, iodine value, peroxide value, and free fatty acid (FFA) content. All analyses were conducted in accordance with standard ASTM procedures[18-21].

Determination of fatty acid profile: The fatty acid composition of the mango kernel oil sample was analyzed directly using a Gas Chromatography–Mass Spectrometry (GC-MS) system (Shimadzu TQ8040, Maryland, USA). Before analysis the oil sample was dissolved in a 4:1 solvent mixture of n-hexane and acetone. The carrier gas, ultra-high-purity helium (99.999%), was given at a continuous flow rate of 1 mL min^{-1}, with a split injection ratio of 4:1.

An aliquot of 100 µL from the prepared sample was injected into the gas chromatographic column at an injector temperature of 250°C. Both the injector and detector were operated at a constant temperature of 280°C. The oven temperature program began at 60°C and was maintained for 5 min before further temperature ramping, followed by a programmed increase at a rate of 5°C min^{-1} to a final temperature of 280°C, without a final holding period. The ion source temperature was maintained at 200°C. Individual fatty acid components were identified by comparing the collected mass spectra to standard reference libraries, taking into account relative peak abundance, molecular weight, molecular formula, and characteristic structural fragments[22,23].

Experimental design: The biodiesel production from mango seed kernel oil was optimized utilizing a Central Composite Design (CCD) inside the Response Surface Methodology (RSM) approach, with Design-Expert version 13 software. This statistical technique was used to identify the best process parameters and evaluate the combined effects of major operating variables on biodiesel output. Table124 summarizes the analysis of four independent parameters across five coded levels (-α, -1, 0, +1, and +α), representing extreme low, low, central, high, and extreme high settings, respectively. The software generated a total of 30 experimental runs. The process variables were methanol-to-oil molar ratio (X_1: 3-15), catalyst concentration (X_2: 1-5 wt%), reaction temperature (X_3: 35-75 °C) and time of reaction (X_4: 30-90 min), as presented in Table-1.

Transesterification reaction: Biodiesel production from mango seed kernel oil was carried out through a homogeneous transesterification process using KOH as the catalyst, with slight modifications to the method described by Kamran *et al.*[25]. The mixture of the reactants, composed of methanol, oil, and catalyst, was placed in a 250 ml beaker on a magnetic hot plate, which ensured controlled heating and continuous stirring at 350 rpm for uniform mixing and temperature regulation. The experimental trials were conducted under varying conditions defined by the Central Composite Design (CCD) matrix (Table-1). Upon completion of the reaction, biodiesel was separated and purified in accordance with the procedure described by Hundie and Akuma[26]. Biodiesel yield was calculated using equation (2).

$$\text{Biodiesel yield (\%)} = \frac{weight\ of\ biodiesel}{weight\ of\ oil} \text{ x } 100 \quad (2)$$

Statistical data analysis: The results of the experiment were statistically evaluated using Design-Expert version 13 software by applying analysis of variance (ANOVA). This method was used to determine the significance of individual process variables, their interaction effects, and their collective influence on the response parameter. The statistical analysis comprised three key components: assessment of lack-of-fit, evaluation of the regression model, and determination of the significance of the model terms. Furthermore, a second-order polynomial equation was established to mathematically represent the experimental conditions and predict the corresponding responses, as presented in Equation (3).

$$Y = \beta_0 \sum_{i=1}^{k} \beta_i x_i + \beta_0 \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{1 \le i \le j}^{k} \beta_{ij} x_i x_j + C \quad (3)$$

Where *Y* is the response (%); 0, *i*, *ii***,** and *ij* are the intercept, linear, quadratic, and interaction coefficients, respectively, while *Xi* and *Xj* are the independent factors.

Results and Discussion

Physicochemical properties of mango Seed kernel oil: The oil extracted from mango seed kernel was evaluated to determine its appropriateness as a raw material for biodiesel production, with the physicochemical parameters presented in Table-2. The extrction yielded 28.14 ± 1.06 wt% of oil, which is comparable to values reported for neem seed (20–25 wt%) and bottle tree seeds (30–31 wt%)[13]. This suggests that mango seed kernels are a viable source of extractable oil, highlighting their potential as a value-added agro-industrial residue for biodiesel production. The measured density of the oil was 825.24 ± 2.56 kg/m³, which is lower than the typical density range of vegetable oils (880–920 kg/m³). This relatively low density could affect both combustion efficiency and energy output, underscoring the necessity of transesterification to improve its performance for biodiesel production[27]. The kinematic viscosity measured at 40°C was 2.71 ± 0.15 mm²/s, which is lower than that of most conventional oils, reflecting favorable flow characteristics[28]. In contrast, the oil exhibited a moisture content of 1.72 ± 0.11%, which is above the recommended limit for biodiesel feedstocks (≤0.5%). Excess moisture can promote hydrolysis, cause soap formation, and lower catalyst efficiency during the transesterification process[26,28]. This suggests that the oil sample should be further dried before transesterification. The iodine value of 102.5mg g^{-1} reflects a moderate degree of unsaturation, which is beneficial for achieving favorable cold-flow properties but may slightly reduce oxidative stability. The free fatty acid (FFA) content was measured at 0.44 ± 0.07%, which falls within the acceptable limit (≤0.5%) for base-catalyzed transesterification. This indicates that the oil can be utilized directly for biodiesel production without the need for extensive pretreatment[27]. However, the peroxide value was 18.54 ± 1.19 meq/kg, exceeding the recommended threshold (<10 meq/kg), which suggests a high tendency toward oxidation and reduced storage stability. Similarly, the acid value (4.15 ± 0.13 mg KOH/g) exceeded the standard range (≤1-2 mg KOH/g). The elevated acid value indicates that, even though the measured FFA content appears lower than the recommended value, the oil still contains enough free fatty acids to negatively influence alkaline-catalyzed biodiesel synthesis. This underscores the relevance of acid value as a more reliable and inclusive parameter for evaluating oil acidity and determining its suitability for base-catalyzed transesterification[29]. This, therefore, suggests pretreatment of the oil before using it for biodiesel production, which counters the earlier suggestion for the result of the free fatty acid.

Response analysis: The transesterification process of mango seed oil catalyzed by potassium hydroxide (KOH) was optimized using a Central Composite Design (CCD) approach. This design was applied to examine the effects of four key operating variables on biodiesel yield, namely the molar ratio of methanoltooil (X_1), catalyst loading (X_2), reaction temperature (X_3), and reaction duration (X_4). Predicted yields ranged from 66.48% to 90.70%, while the experimental results varied between 67.20% and 91.94% (Table-3). These findings confirm that mango kernel oil is a viable non-food oil with significant potential for the synthesis of biodiesel under optimized conditions. The highest yield of 91.94% was obtained at a methanol-to-oil ratio of 9:1, catalyst concentration of 3 wt%, reaction temperature of 55 °C, and reaction time of 60 minutes (Run 1). In contrast, the lowest yield of 67.20% was recorded at 75 °C (Run 21), indicating that elevated temperatures may lower efficiency due to methanol loss through evaporation or possible thermal degradation[30]. The maximum yield observed aligns closely with the 91.38% yield reported by Subhash and Ragit[31] for sesame oil biodiesel production under optimized conditions using Design of Experiment (DOE) techniques.

Table-1: Central Composite Design (CCD) with coded and actual values of experimental parameters of the design matrix used in the production of biodiesel for all the samples.

Independent variables	Symbols	Coded levels				
		-α	-1	0	1	+α
Methanol to oil molar ratio (mol)	X_1	3:1	6:1	9:1	12:1	15:1
Catalyst concentration (wt.%)	X_2	1.0	2.0	3.0	4.0	5.0
Temperature (°C)	X_3	35.0	45.0	55.0	65.0	75.0
Time of reaction (min)	X_4	30.0	45.0	60.0	75.0	90.0

Statistical validation using ANOVA and model fit statistics (Table-4) confirmed the reliability of the results. The developed quadratic model was highly statistically significant, with an F-value of 206.14 and a corresponding p-value below 0.0001. In contrast, the lack-of-fit test was insignificant ($p = 0.132 > 0.05$), implying that the model provided an adequate and reliable representation of the experimental results. The coefficient of determination ($R^2 = 0.9948$), together with the adjusted R^2 (0.9900) and predicted R^2 (0.9702), indicated a strong correlation between the predicted and experimental results. In addition, the adequate precision value of 46.17, well above the acceptable threshold of 4, confirmed a high signal-to-noise ratio. The low coefficient of variation (C.V. = 1.01%) and small standard deviation (0.7945) further demonstrated excellent reproducibility of the model. This was supported by the parity plot (Figure-3), which displayed a close match between predicted and actual biodiesel yields, validating the model's accuracy in predicting outcomes across the design space. This is in conformity with the result reported by Onyia *et al*.[24] where the residual plot showed a strong correlation between experimental and predicted yields, with an R^2 value of 0.9955, close to one. The model equation in terms of the coded values of the process parameters and biodiesel yield (Y) is given by Equation (4).

$$Y = 71.89 - 5.08708A + 2.02625B - 5.25708C - 0.59875D + 0.426875AB - 1.17937AC + 0.975625AD - 0.588125BC + 1.13437BD + 2.17323A^2 + 2.18448B^2 + 2.17323C^2 + 2.17323D^2 \quad (4)$$

The regression analysis revealed that all linear terms, except catalyst concentration (B), had negative coefficients. In contrast, the interaction terms methanol-to-oil ratio × temperature (AC) and catalyst concentration × temperature (BC), as well as all quadratic terms, carried positive coefficients. This implies that increasing variables with negative coefficients lowers biodiesel yield, whereas increases in variables with positive coefficients improve the yield.

Individual effects of transesterification variables: The perturbation plots (Figure-4) demonstrate the influence of each process parameter on the yield of the biodiesel. Temperature exerted the most pronounced influence, followed by the methanol-to-oil molar ratio, as indicated by the steep slopes of their respective curves. This observation aligns with the ANOVA findings, where temperature (X_3) was identified as the most significant factor ($F = 1050.78$, $p < 0.0001$), followed by methanol-to-oil ratio (X_1) and catalyst concentration (X_2). Although reaction time (X_4) had a comparatively smaller impact, it was still statistically significant ($F = 13.63$, $p = 0.0022$), confirming that all four variables contributed meaningfully to yield optimization.

The interaction effect of the transesterification reaction: The 3D response surface plots (Figure-5) depict the interactive effects of the process variables on biodiesel yield. While simultaneous optimization of all four parameters produced the highest yield of 91.94%, the maximum yields obtained from individual two-factor interactions were generally below 80%. This underscores the importance of multivariate optimization in attaining maximum conversion efficiency. For instance, Figure-5(a) indicates that biodiesel yield increased with higher catalyst concentration and methanol-to-oil ratio, achieving about 78-79% at approximately 1.0 wt% catalyst and a 9:1 ratio. Likewise, Figure-5(b) shows that the yield improved with rising temperature and molar ratio, reaching an optimum of around 78% at 60°C and a 9:1 ratio. Beyond 60°C, however, further temperature increases led to only marginal gains or slight reductions in yield, likely due to methanol loss through evaporation[32]. Figure-5(c) shows the combined effect of reaction time and the methanol-to-oil molar ratio on biodiesel yield. An increase in reaction time led to a corresponding rise in yield, which reached an optimum value of approximately 77–78% at a reaction time of 60 min and a molar ratio of 9:1. Likewise, Figure-5(d) presents the interaction between reaction temperature and catalyst concentration, showing a gradual enhancement in biodiesel yield that attained a maximum of about 78% at 60°C and a catalyst loading of 1.0 wt%.

Optimization of process parameters and model validation: Process optimization and model validation were carried out using Central Composite Design (CCD) with a numerical desirability function. The independent variables were varied within specified ranges, while the dependent variable (biodiesel yield) was targeted formaximization to identify optimal conditions. The model predicted the following optimal parameters: 2.8 wt% catalyst concentration, 9.5:1 methanol-to-oil ratio, reaction temperature of 61°C, and reaction time of 60 min, corresponding to a predicted yield of 90.35%. Experimental validation under these conditions, performed in triplicate, produced an average yield of 91.91% with a small error margin of 1.72%. These findings verify the robustness and accuracy of the CCD model in optimizing transesterification parameters for maximum biodiesel production.

Table-2: Physicochemical properties of extracted oil from mango seed kernel.

Parameters	Composition
Yield (wt%)	28.14 ± 1.06
Density (kg/m^3)	825.24 ± 2.56
Viscosity@40 ^oC (mm^2 /s)	2.71 ± 0.15
Moisture (%)	1.72 ± 0.11
Iodine value ($mg\ g^{-1}$)	102.5 ± 1.08
Free fatty acid (%)	0.44 ± 0.07
Peroxide value (meq / kg)	18.54 ± 1.19
Acid value (mgKOH/ g)	4.15 ± 0.13
Saponification value (mgKOH/g)	201.13±1.01

Table-3: Fatty acid profiles of mango seed kernel oil.

Fatty acid (%)	MW (g/mol)	Formula	Composition (%)
Lauric acid (C12:0)	200	$C_{12}H_2O_2$	2.70
Palmitic acid (C16:0)	256	$C_{16}H_{34}O_2$	6.98
Stearic acid (C18:0)	284	$C_{18}H_{36}O_2$	18.17
Arachidic acid (C20:0)	312	$C_{20}H_{40}O_2$	4.90
Palmitoleic (C16:1)	254	$C_{16}H_{32}O_2$	1.68
Oleic acid (C18:1)	282	$C_{18}H_{34}O_2$	40.16
Gadoleic (C20:1)	310	$C_{20}H_{38}O_2$	2.48
Tricosenoic acid (C23:1)	322	$C_{23}H_{46}O_2$	1.46
Linoleic acid (C18:2)	280	$C_{18}H_{32}O_2$	8.11
α-Linolenic acid (C18:3)	278	$C_{18}H_{30}O_2$	6.39

MW: molecular weight, ND: not detected

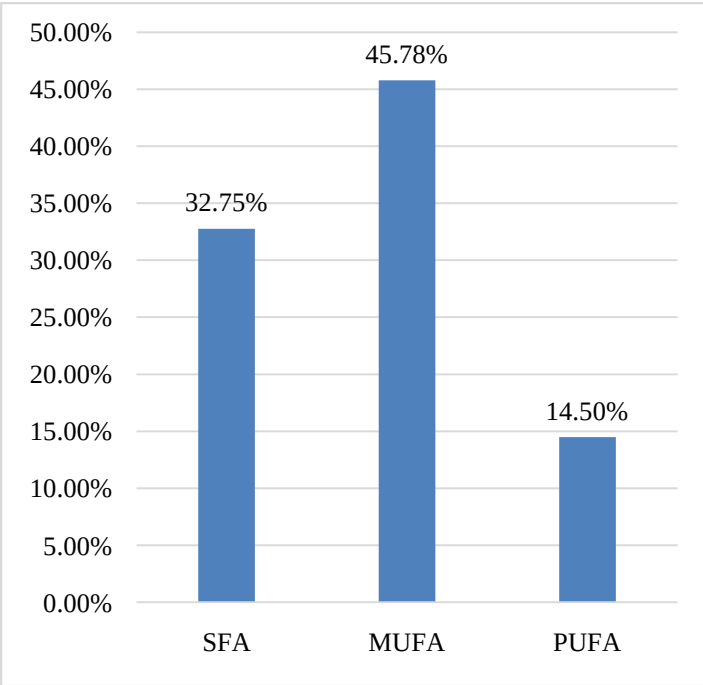


Figure-1: Fatty acids classification based on degree of saturation.

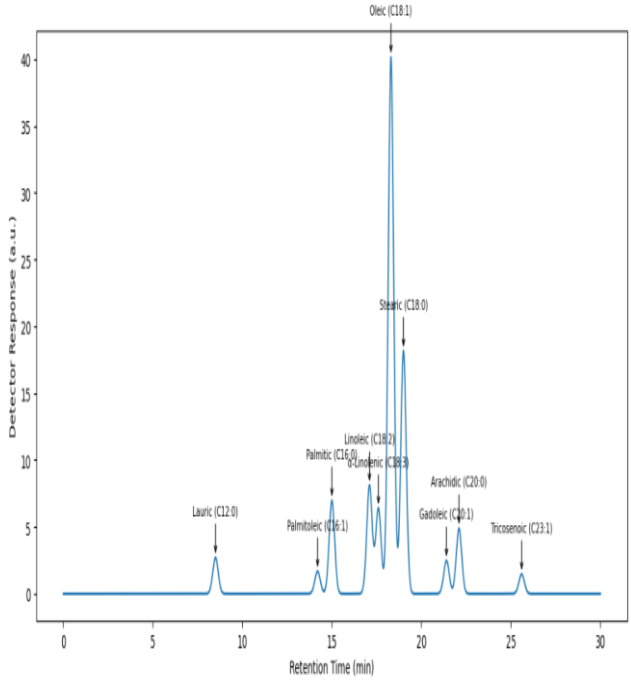


Figure-2: Chromatogram peaks of the fatty acid profile obtained from the GC-MS.

Table-4: Experimental design (CCD) matrix and the actual and predicted values of the biodiesel yield produced from mango kernel oil using KOH as a catalyst.

No of runs	X_1	X_2	X_3	X_4	Experimental yield (%)	Predicted yield (%)
1	9:1	3.0	55.0	60.0	91.94	90.76
2	9:1	5.0	55.0	60.0	85.62	84.68
3	6:1	2.0	65.0	45.0	81.85	82.20
4	3:1	3.0	55.0	60.0	87.02	86.47
5	12:1	4.0	65.0	45.0	71.89	71.89
6	6:1	2.0	45.0	75.0	71.89	71.89
7	9:1	3.0	55.0	60.0	68.63	67.93
8	6:1	4.0	45.0	75.0	71.89	71.89
9	9:1	1.0	55.0	60.0	71.89	71.89
10	9:1	3.0	55.0	30.0	71.89	71.89
11	12:1	4.0	45.0	75.0	69.63	69.40
12	6:1	2.0	65.0	75.0	72.02	72.47
13	6:1	4.0	65.0	30.0	83.00	83.03
14	9:1	3.0	55.0	60.0	82.32	83.27
15	9:1	3.0	55.0	90.0	75.96	76.58
16	12:1	4.0	65.0	75.0	69.73	70.07
17	9:1	3.0	55.0	60.0	78.40	77.91
18	12:1	2.0	65.0	45.0	91.76	91.10
19	12:1	2.0	45.0	45.0	71.89	71.89
20	15:1	3.0	55.0	60.0	91.29	92.41
21	9:1	3.0	75.0	60.0	67.20	66.48
22	12:1	2.0	45.0	75.0	79.32	79.39
23	6:1	4.0	45.0	45.0	90.86	91.48
24	12:1	4.0	45.0	45.0	84.20	84.83
25	6:1	2.0	45.0	45.0	82.17	81.78
26	12:1	2.0	65.0	75.0	78.22	78.12
27	9:1	3.0	55.0	60.0	90.84	90.31
28	9:1	3.0	55.0	60.0	79.64	79.69
29	6:1	4.0	65.0	75.0	69.55	70.41
30	9:1	3.0	35.0	60.0	83.09	83.50

Note: A = X_1 : methanol/oil molar ratio, B = X_2 : catalyst concentration (wt%), C = X_3 : Temperature (^oC) and X_4: reaction time (min).

Table-5: ANOVA and fit statistics results obtained from the quadratic model for the production of biodiesel from the mango seed oil.

Source	SS	DF	MS	F-value	p-value	
Model	1821.71	14	130.12	206.14	< 0.0001	Significant
A-Methanol to oil	621.08	1	621.08	983.92	< 0.0001	
B-Catalyst concentration	98.54	1	98.54	156.10	< 0.0001	
C-Temperature	663.29	1	663.29	1050.78	< 0.0001	
D-Reaction time	8.60	1	8.60	13.63	0.0022	
AB	2.92	1	2.92	4.62	0.0484	
AC	22.25	1	22.25	35.26	< 0.0001	
AD	15.23	1	15.23	24.13	0.0002	
BC	5.53	1	5.53	8.77	0.0097	
BD	20.59	1	20.59	32.62	< 0.0001	
CD	0.0127	1	0.0127	0.0201	0.8893	
A^2	129.54	1	129.54	205.22	< 0.0001	
B^2	130.89	1	130.89	207.35	< 0.0001	
C^2	129.54	1	129.54	205.22	< 0.0001	
D^2	129.54	1	129.54	205.22	< 0.0001	
Residual	9.47	15	0.6312			
Lack of Fit	7.64	10	0.9468	2.59	**0.132**	Not significant
Pure Error	1.83	5	0.366			
Cor Total	1831.18	29				
Std. Dev.	0.7945					
Mean	78.85					
C.V. %	1.01					
R^2	0.9948					
Adjusted R^2	0.9900					
Predicted R^2	0.9702					
Adeq Precision	46.1703					

Note: SS = sum of square, DF= degree of freedom, MS= mean square A = X_1: methanol/oil molar ratio, B = X_2: catalyst concentration (wt%), C = X_3 : Temperature (^oC) and X_4: reaction time (min).

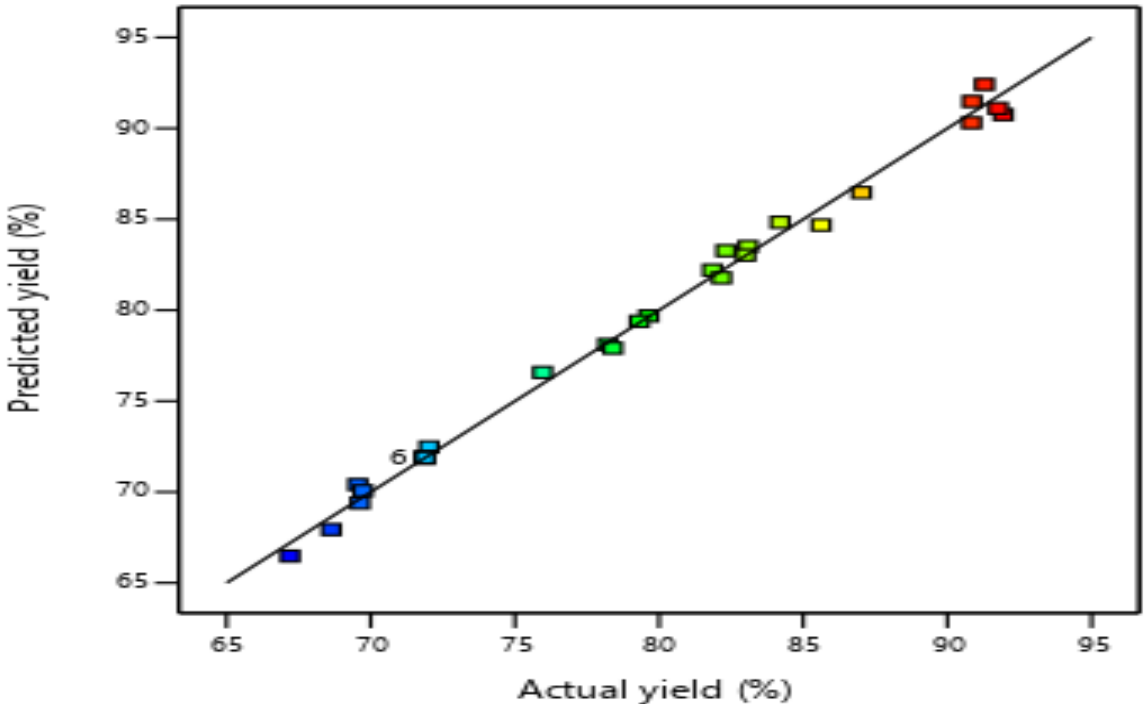


Figure-3: Experimental yield against predicted yield for the biodiesel produced from mango seed oil.

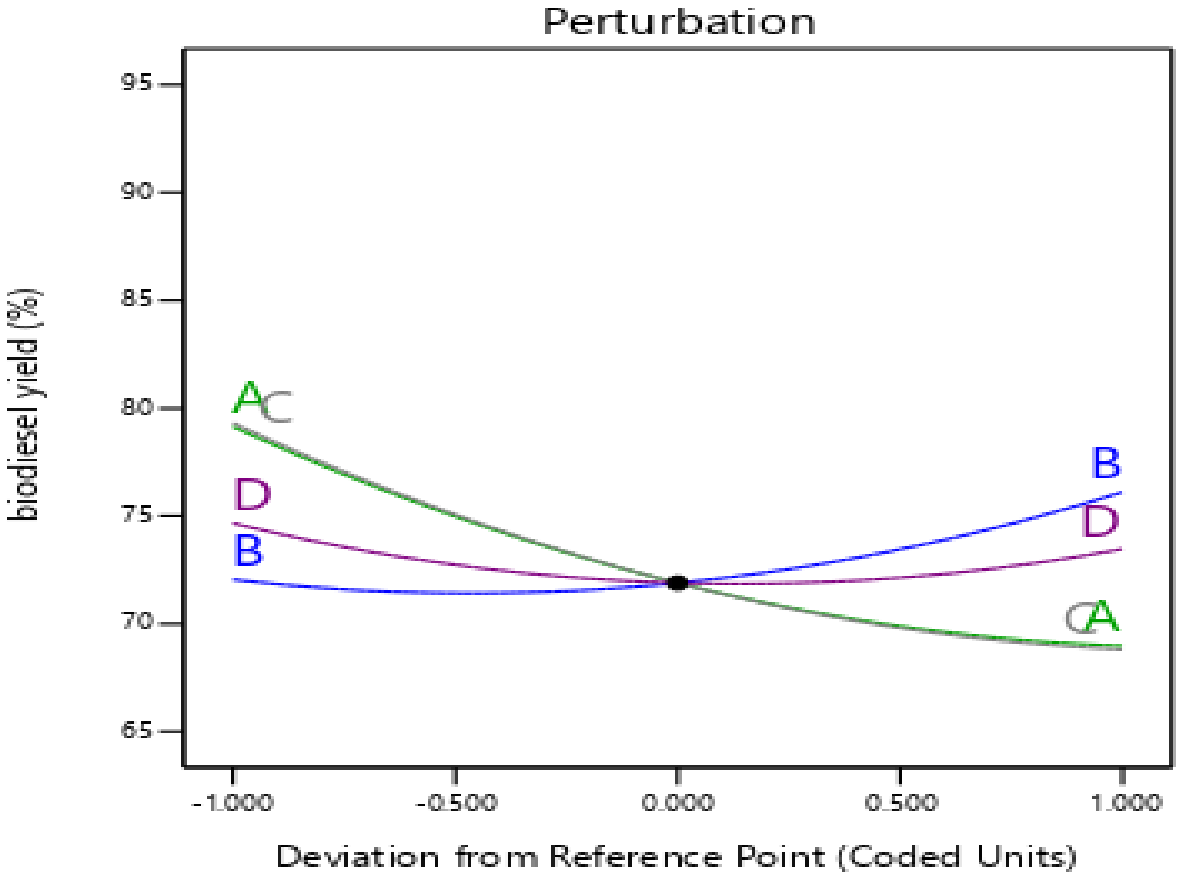


Figure-4: Effect of process parameters on biodiesel production from mango seed oil (A = X_1: methanol/oil molar ratio, B = X_2: catalyst concentration (wt%), C = X_3: Temperature (^oC), and X_4: reaction time (min).

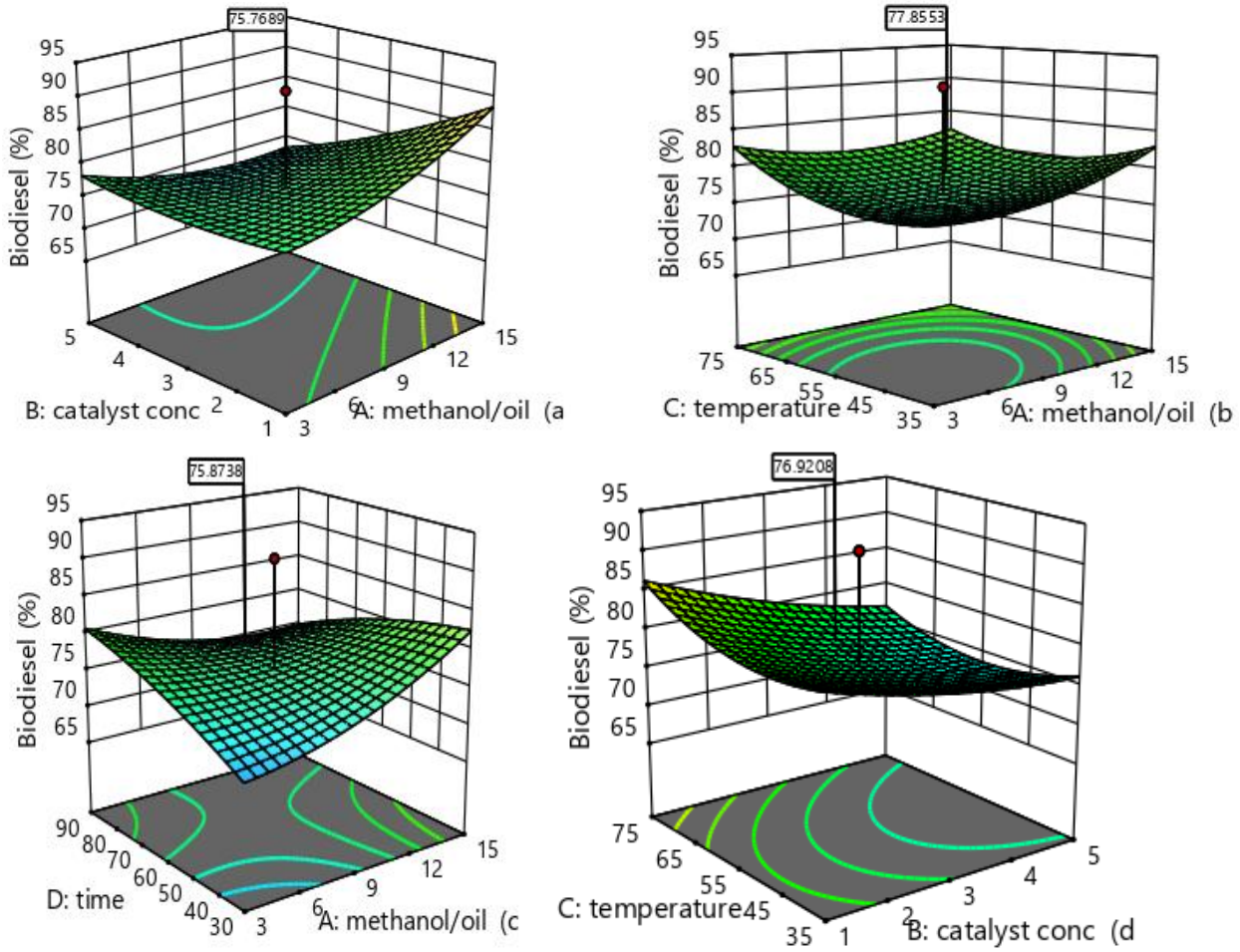


Figure-5: 3D plots showing the Effects of (a) catalyst concentration (wt%) against methanol/oil molar ratio (b) temperature (^{o}C) against methanol /oil molar ratio (c) reaction time (min) against methanol/oil (wt%) and (d) temperature (^{o}C) against catalyst concentration (wt%) on the biodiesel yield produced from mango seed oil.

Table-6: Physicochemical properties of the biodiesel produced from the mango seed kernel oil using KOH catalyst and ASTM standards.

Parameters	Mango seed	ASTM
Density(kg/m^3)	799.4 ± 2.16	860-900
Specific gravity	0.80 ± 0.03	0.88
viscosity@ 40 ^{o}C (mm^2 /s)	2.60 ± 0.11	1.9 - 6.0
Moisture (%)	0.04 ± 0.01	≤ 0.05
Pour point (^{o}C)	-6.54±1.25	-5 -10
Flash point (^{o}C)	110.0 ± 2.18	≥130
Iodine value (mg g^{-1})	46.86±1.64	≤120
Acid value (mgKOH/g)	0.88 ± 0.12	0.1-0.5
Calorific value (MJ/kg)	23.10± 1.85	37- 40
Cetene number (min)	51.00 ±1.24	48- 65

Physicochemical characteristics of the produced biodiesel: The physicochemical properties of biodiesel obtained from mango kernel oil using a KOH catalyst were evaluated against ASTM D6751 standards (Table-3). The results showed that although several parameters met the required specifications, certain deviations highlighted both the advantages and limitations of mango seed oil as a biodiesel feedstock. The measured density was 799.4 ± 2.16 kg/m³, which falls below the ASTM range of 860-900 kg/m³. Likewise, the specific gravity (0.80 ± 0.03) was lower than the recommended value of 0.88, indicating a reduced volumetric energy content that may negatively influence combustion efficiency and fuel injection in compression ignition engines[32]. Conversely, the kinematic viscosity at 40°C was 2.60 ± 0.11mm²/s, which lies within the ASTM specified range of 1.9-6.0 mm²/s. This indicates favorable flow and atomization properties, crucial for efficient combustion and reduced engine deposits[33]. The moisture content of the biodiesel (0.04 ± 0.01%) met the ASTM maximum limit of 0.05%, indicating a reduction in the risk of microbial contamination, corrosion, and instability[34,35]. However, the flash point was 110.0 ± 2.18°C, lower than the ASTM requirement of 130°C, which raises safety concerns related to volatility and storage[35]. The acid value of 0.88 ± 0.12 mg KOH/g exceeded the ASTM specification of 0.1-0.5 mg KOH/g, suggesting a higher concentration of free fatty acids that could contribute to corrosion and deposit formation in fuel systems[36]. A significant limitation was the calorific value, measured at 23.10 ± 1.85 MJ/kg, which is considerably below the ASTM standard range of 37–40 MJ/kg. This reduction reflects lower energy content per unit mass, potentially leading to reduced engine performance and increased fuel consumption[33]. In contrast, the cetane number (51.00±1.24) met the ASTM standard of 48–65, confirming satisfactory ignition quality and efficient combustion[37].

Conclusion

The mango seed kernel oil sample provided a moderate extraction yield and exhibited favorable cold flow properties. However, its elevated moisture, peroxide, and acid values pose notable challenges. These limitations suggest that pretreatment measures such as drying, neutralization, and antioxidant addition are necessary to improve stability and processing efficiency. The biodiesel produced from mango seed kernel oil complied with several ASTM specifications, including viscosity, moisture content, iodine value, and cetane number, indicating partial suitability for fuel applications. Nonetheless, shortcomings such as low density, reduced calorific value, high acid value, and a flash point below the ASTM limit constrain its direct use as a standalone biodiesel. To address these issues, blending with petroleum diesel or higher-quality biodiesels is recommended to improve safety and performance. Overall, mango seed oil demonstrated effective conversion into biodiesel under optimized KOH-catalyzed conditions. The quadratic model developed in this study proved robust and reliable for process optimization, underscoring the potential of mango seed oil as a sustainable, non-edible feedstock for biodiesel production.

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