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OPTIMIZATION OF BIODIESEL PRODUCTION FROM MANGO SEED
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ABSTRACT

The increasing need for second generation feedstocks for biodiesel production due to the drawbacks associated with edible oil-based biodiesel has led to the use of non-edible feedstocks like mango seed kernel oil (MSKO). The objectives of this research are to improve the biodiesel production from MSKO through transesterification process and to maximize the biodiesel yield as well as the calorific value of the biodiesel. Four factors, namely methanol-to-oil ratio (4:1, 6:1, 8:1 and 10:1), reaction temperature (45°C, 50°C, 55°C and 60°C), reaction time (30 min, 60 min, 90 min and 120 min) and catalyst concentration (0.5%, 1.0%, 1.5% and 2.0%) were chosen and studied at four levels using Taguchi's L16 orthogonal array. A multi-objective optimization approach was used in this study by applying the WSM on the response variables that were normalized and weighted (yield 0.6 and calorific value 0.4). The findings indicated that the best conditions for transesterification were methanol to oil ratio of 8:1, temperature of 55°C, time of 120 minutes and catalyst concentration of 1.5% to yield biodiesel of 96.15% and calorific value of 39.67 MJ/kg. Under these optimal conditions, confirmation tests were conducted which gave nearly similar results ($96.16 \pm 0.07\%$ yield and 39.70 ± 0.08 MJ/kg calorific value) thereby confirming the effectiveness of the optimization process. Analysis of variance (ANOVA) revealed that reaction temperature has an effect on calorific value at $p < 0.05$ while other parameters have a combined effect on yield. This study shows that MSKO is a feasible feedstock for biodiesel production that is not suitable for human consumption and provides a statistically significant model for improving the quality of the fuel and the efficiency of the conversion process.



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I. INTRODUCTION

Biodiesel is an environment friendly, renewable and sustainable fuel that has been developed to meet the rising energy demands and environmental pollution. While diesel is a non renewable resource derived from petroleum, biodiesel is produced from renewable resources such as vegetable oils, animal fats, and waste cooking oils, and therefore can be a carbon neutral fuel that can help in the reduction of greenhouse gases emissions [1]. The environmental benefits of biodiesel include the ability to reduce carbon monoxide, hydrocarbons, and particulate matter emissions and the fact that biodiesel is more biodegradable than fossil diesel [2–4]. Besides the environmental impacts, biodiesel has the advantages of energy security since it helps to cut on the importation of fossil fuels and diversification of energy. The exhaustion of fossil fuel resources and fluctuations in prices have encouraged researchers and policymakers to search for biofuels as an effective solution [5], [6]. Moreover, biodiesel from waste like used cooking oil and municipal sewage sludge has attracted interest due to its potential to address waste management challenges while offering a viable biofuel source [7], [8]. The global consumption of biodiesel is on the rise due to the enhanced environmental standards and international agreements on emissions of carbon.

Today, most countries have opted to blend different percentages of biodiesel with the main stocks which include the B5 (5% biodiesel), B10 (10%) and the B20 (20%) to move towards low-carbon fuels in the transport sector [9]. As feedstocks for biodiesel production are becoming more diverse, catalysts are being improved, and the process is being optimized, biodiesel production is expected to become more efficient and large-scale, which will play an important role in the transition to clean energy [10], [11]. The use of edible oils in biodiesel production has some drawbacks such as competition with food resources, increasing costs, and negative impacts on the environment such as deforestation and loss of bio-diversity [12]. To address these challenges, non-edible oils like *Jatropha*, *Karanja*, and MSKO have been considered because of their availability, cheap, and do not compete with food resources [13–15]. Of these, MSKO is more attractive because of its high oil content of 8–15% which makes it possible to use it as feedstock instead of the conventional feedstocks [16], [17]. Moreover, MSKO is easily accessible and can be procured without any extra land requirement and resources hence making it sustainable [18], [19]. Based on these benefits, MSKO can be considered as a viable and untapped feedstock that is in line with the waste-to-energy and biofuel development trends around the world [20].

The conversion of MSKO into biodiesel is a challenge since it contains high FFA that results in soap formation and deactivation of the catalyst [21], [22]. Therefore, the factors such as methanol to oil ratio, catalyst concentration, reaction temperature, and reaction time are important in determining the biodiesel yield and quality [23]. Lower methanol-to-oil ratio lead to partial conversion of feedstock, while higher ratio make the separation process more challenging [24]. Low concentration of the catalyst results in low conversion while high concentration results in the formation of soap [25]. Also, reaction temperature and time must be well controlled to achieve maximum conversion of the triglycerides to biodiesel without undergoing thermal breakdown [26]. Addressing these challenges by improving the process and catalysts would go a long way in increasing the yield of biodiesel, the economics of the process and sustainability. The enhancement of biodiesel production and performance of mango seed biodiesel has been investigated using various techniques to increase the yield, fuel properties, and engine performance. Transesterification has been widely used in biodiesel synthesis and [27] used RSM to optimize the MSKO biodiesel production with a 95% yield that conforms to the international fuel standards. In the same vein, [28] also showed that the biodiesel obtained from MSKO meets the ASTM-D6751 and EN14214 standards in terms of physicochemical characteristics and engine performance as well as conventional diesel. Building on biodiesel sources, [29] used mango seed kernel and tamarind seed biomass waste and achieved biodiesel yield of 75–80% which is in line with ASTM D6751 standard for waste-to-energy solutions.

In addition to the production optimization, several works have been done on the improvement of the properties of mango seed biodiesel for use in diesel engines. [30] blended hybrid nanoparticles (Al_2O_3 , TiO_2) and hydrogen gas into Mango Seed Methyl Ester emulsified biodiesel using RSM and Deep Recurrent Neural Network-based Honey Badger Algorithm to reach 32% Brake Thermal Efficiency and enhanced combustion properties with $\text{RMSE} \leq 6.6$. Moreover, [30] enhanced MSME20 biodiesel with cerium oxide and magnesium oxide nanoparticles and achieved the reduction of CO, HC, and smoke emissions by 28%, increase in BTE by 16%, and optimization of NO_x emission using a hybrid deep belief network-sandpiper optimizer. There have also been attempts to increase the biodiesel yield through other methods of optimization in recent years. [31] used ultrasound supported methanolysis and Whale Algorithm to synthesize biodiesel from waste mango seed kernel oil with 90.88% yield which is higher than transesterification and RSM. This paper aims at evaluating the biodiesel production from mango seed kernel oil through the evaluation of the transesterification parameters using Taguchi based experimental design and WSM optimization. Although there are many studies on biodiesel production, few research works address the effects of methanol-to-oil ratio, reaction temperature, reaction time, and catalyst concentration simultaneously using multiple objectives with biodiesel yield and calorific value. The novelty of this work is based on the combined statistical and decision-making approach that increases the efficiency of the process and guarantees the quality of the fuel. In the present work, Taguchi L16 orthogonal array was used to plan the experiments and ANOVA analysis was performed to find out the significance of each parameter to develop an efficient biodiesel production process.

II. MATERIALS AND METHODOLOGY

This section describes the experimental methodology and analytical methods used in the enhancement of biodiesel production from mango seed kernel oil. It also provides information on feedstock pre-treatment, transesterification process, experimental design, and statistical analysis to assess the biodiesel production efficiency and fuel properties.

II.1 EXTRACTION OF MANGO SEED KERNEL OIL

The mango seeds used in this study were sourced from the Western Maharashtra region of India for the extraction of oil. To remove the surface contamination and other unwanted substances, the seeds were washed with water before the process. The cleaned seeds were then dried in two stages to minimize moisture content and improve the efficiency of extraction of oil. In the first drying stage, the seeds were exposed to direct sunlight for 36 hours to undergo natural drying process. This was succeeded by oven drying at 65°C for 3 hours in order to ensure that the samples were evenly and thoroughly dried. After that, the seeds were dried and the kernels were separated from the hard-outer shells by using hydraulic pressing mechanism. In order to get the maximum yield of oil, the extracted kernels were dried at 60°C for 3 hours. After that, the completely dried kernels were taken through mechanical oil extraction mill. This process gave about 130g of oil per kilogram of the mango kernels with an extraction efficiency of 13%. The extracted MSKO was then filtered and placed in a closed container to avoid any oxidation and degradation of the sample before the next process. The process of extraction of oil from the raw mango seeds is illustrated in the Figure 1.

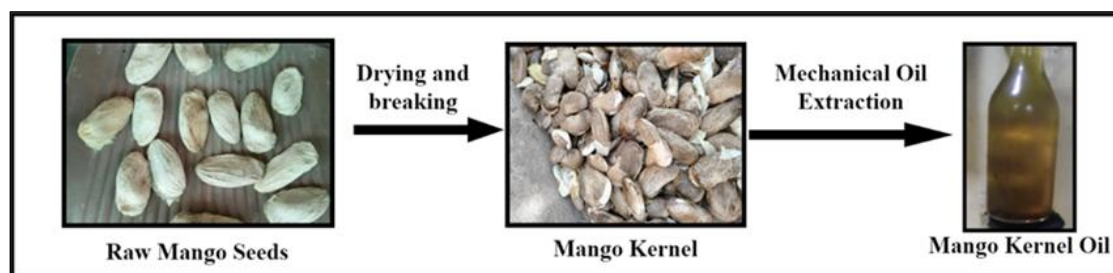


Figure 1. Extraction of Mango Seed Oil Kernel.

Source: Authors, (2026).

II.2 TRANSESTERIFICATION PROCESS

The biodiesel production from MSKO was carried out in a batch reactor by using methanol and potassium hydroxide (KOH) as a catalyst to catalyse the transesterification of the triglycerides into FAME. The reaction was started by dissolving the catalyst in methanol to make a solution which was then charged into the preheated MSKO. In order to understand the effect of reaction conditions on biodiesel yield and the overall process, the reaction conditions were altered successively. Four factors were taken into consideration for the transesterification process: methanol to oil molar ratio, temperature, time and catalyst concentration. Each of these parameters was tested at four different levels to find the best level that would give the highest biodiesel conversion. The parameters and their levels are as follows: The detailed parameters and their levels are presented in Table 1.

Table 1. Transesterification process parameters and levels.

Parameter	Level 1	Level 2	Level 3	Level 4
Methanol-to-Oil Ratio	04:01	06:01	08:01	10:01
Reaction Temperature (°C)	45°C	50°C	55°C	60°C
Reaction Time (Min)	30 min	60 min	90 min	120 min
Catalyst Concentration (% w/w)	0.50%	1.00%	1.50%	2.00%

Source: Authors, (2026).

The reaction mixture was stirred at 600 rpm to facilitate emulsification and increase mass transfer rates so that the reactants could come into close contact. After completion of the reaction, the mixture was transferred to a separation funnel and allowed to settle for 12 hours in order to allow the glycerol, the major by-product to settle at the bottom of the funnel from the biodiesel layer. The upper biodiesel layer was then separated and washed several times with warm distilled water (50°C–60°C) in order to remove catalyst, methanol and soap formation. Last but not the least, the biodiesel was then heated at a temperature of 105°C with a pressure of 600 mmHg for 30 minutes to remove water content. The biodiesel product was then filtered and kept in sealed containers for further physicochemical and performance tests to determine its viability as a renewable energy source.

II.3 EXPERIMENTAL DESIGN

In order to improve the biodiesel production process from MSKO, the Taguchi L16 orthogonal array was used as an experimental design method. This approach allows for the determination of the best combination of factors that would yield the most optimal result since it involves the manipulation of more than one factor at a time while at the same time reducing the number of trials. The four factors that were considered in this study were the methanol to oil ratio, temperature, time and concentration of the catalyst and each of these factors was set at four different levels. By conducting the experiment using the L16 orthogonal array, 16 trials were conducted instead of 256 (4⁴) in a full factorial design which saved time, cost and resources yet achieving the best optimization. The Taguchi L16 experimental matrix used in this study is shown in Table 2 which indicates 16 different combinations of the process parameters.

Table 2. Taguchi L16 orthogonal array for biodiesel optimization

Run	Methanol-to-Oil Ratio (Molar Ratio)	Reaction Temperature (°C)	Reaction Time (Minutes)	Catalyst Concentration (% w/w)
1	04:01	45	30	0.5
2	04:01	50	60	1
3	04:01	55	90	1.5
4	04:01	60	120	2
5	06:01	45	60	1.5
6	06:01	50	30	2
7	06:01	55	120	0.5
8	06:01	60	90	1
9	08:01	45	90	2
10	08:01	50	120	1.5
11	08:01	55	30	1
12	08:01	60	60	0.5
13	10:01	45	120	1
14	10:01	50	90	0.5
15	10:01	55	60	2
16	10:01	60	30	1.5

Source: Authors, (2026).

This orthogonal array design makes it possible to efficiently analyze the effects of each factor with least replication of experiments. The outcomes of these trials were used in determining the best reaction parameters that would yield the highest biodiesel yield with the best quality. The gross energy content of each biodiesel sample was determined by employing the Parr 6400 bomb calorimeter as per the ASTM D240 method. About one gram of the sample was burned in a combustion chamber under controlled oxygen environment, and the heat generated was used in determining the higher heating value.

II.4 STATISTICAL ANALYSIS

In order to determine the effect of the transesterification parameters on biodiesel yield and calorific value, the Analysis of Variance (ANOVA) was used as the statistical tool. The factors that were used in this study were methanol-to-oil ratio, reaction temperature, reaction time and catalyst concentration and they were set at four levels with the help of Taguchi L16 orthogonal array. To check the significance of each factor, ANOVA was performed separately for both output variables. The study was conducted at 95% confidence level and the $p < 0.05$ was used to determine statistical significance. The F-value was used to compare the significance of each parameter while the sum of squares determined the extent of contribution of each factor to the total variability. This approach helped in determining the key variables influencing the biodiesel production and facilitated the confirmation of the experimental results on the basis of statistical analysis.

II.5 OPTIMIZATION USING WEIGHTED SUM METHOD

In order to determine the best conditions for biodiesel production from mango seed kernel oil through transesterification process, the WSM was used as a multi-objective optimization technique. This makes it possible to combine two or more output variables such as biodiesel yield (%) and calorific value into a single decision variable by use of weights and normalization. This is especially useful when the optimization is done for both, the process and the fuel quality at the same time. The optimization was done using a Taguchi L16 orthogonal array, in which four factors, namely methanol to oil ratio, reaction temperature, reaction time and catalyst concentration were varied at four levels. The results of each experimental run were obtained in terms of the performance outputs to assess the efficiency of the process. The output variables are in different units and scales and therefore, normalization was necessary to transform all the variables to a single dimensionless scale. The normalization techniques that were used were based on the nature of the criteria as follows:

For beneficial criteria (higher values are better), such as biodiesel yield and calorific value:

$$X_{\text{norm}} = \frac{X_i}{X_{\text{max}}} \quad (1)$$

For non-beneficial (cost) criteria (lower values are better), the formula would be:

$$X_{\text{norm}} = \frac{X_{\text{min}}}{X_i} \quad (2)$$

However, in this study, both output variables are beneficial, so only the first normalization equation was used. After normalization, the output variables were then scaled to a suitable value in order to represent the importance of each of the output variables. According to the objectives of the study, biodiesel yield was assigned a weight of 0.6 since it is directly related to production while calorific value was assigned a weight of 0.4 since it is an indication of fuel quality. The weighted sum score for each experimental run was calculated using the following equation:

$$S_i = \sum_{j=1}^n w_j \cdot X_{ij}^{\text{norm}} \quad (3)$$

Where

S_j = weighted sum score for the i^{th} experimental run

w_j = weight of the j^{th} response variable

X_{ij} = normalized value of the j^{th} response in the i^{th} run

n = number of response variables (2 in this case)

III. RESULT AND DISSCUSION

This section focuses on the findings of the experimental study and optimization of biodiesel production from mango seed kernel. In the present work, the biodiesel yield and calorific value are studied as functions of transesterification parameters with the help of statistical and multi-objective approaches. The validity of the optimal conditions is confirmed by the results of the confirmation tests of key findings.

III.1 EXPERIMENTAL TEST RESULTS

The findings in Table 3 show the effect of transesterification process variables, namely, methanol to oil ratio, reaction temperature, reaction time and catalyst concentration on biodiesel production and calorific value. The highest biodiesel yield of 96.15% was obtained at a methanol-to-oil ratio of 8:1, reaction temperature of 50°C, reaction time of 120 minutes, and catalyst concentration of 1.5% which suggests that the optimal methanol ratio and an optimum catalyst concentration along with an adequate reaction time is suitable for the maximum conversion of triglycerides. The least yield of 72.44% was obtained at a methanol to oil ratio of 4:1, reaction temperature of 45°C, reaction time of 30 minutes and catalyst concentration of 0.5% as the low concentration of methanol and the low concentration of the catalyst hinders the transesterification reaction hence low biodiesel yield.

Table 3: Experimental results showing effect of process parameters on response variables.

Run	Methanol-to-Oil Ratio (Molar Ratio)	Reaction Temperature (°C)	Reaction Time (Minutes)	Catalyst Concentration (% w/w)	Yield (%)	CV (MJ/kg)
1	04:01	45	30	0.5	72.44	38.92
2	04:01	50	60	1	84	39.19
3	04:01	55	90	1.5	91.63	39.59
4	04:01	60	120	2	75.29	39.4
5	06:01	45	60	1.5	91.89	39.22
6	06:01	50	30	2	79.54	39.38
7	06:01	55	120	0.5	84.46	39.56
8	06:01	60	90	1	90.86	39.76
9	08:01	45	90	2	85.1	39.38
10	08:01	50	120	1.5	96.15	39.67
11	08:01	55	30	1	88.81	40.1
12	08:01	60	60	0.5	82.52	39.61
13	10:01	45	120	1	89.07	39.45
14	10:01	50	90	0.5	84.79	39.22
15	10:01	55	60	2	90.73	39.72
16	10:01	60	30	1.5	85.45	39.68

Source: Authors, (2026).

The calorific value which defines the energy content of the fuel was found to be in the range of 38.92 MJ/kg to 40.1 MJ/kg in all the experimental trials. The highest calorific value of 40.1 MJ/kg was achieved at the methanol to oil ratio of 8:1, reaction temperature of 55°C, reaction time of 30 minutes and catalyst concentration of 1% which shows that moderate conditions yield biodiesel with high energy content. But the yield of biodiesel and calorific value were not in a straight line because some of the experimental run with high yield had low calorific values. This implies that biodiesel yield is affected mostly by the efficiency and the extent of the transesterification process while calorific value is more determined by the quality and the chemical makeup of the fatty acid methyl esters produced during the process. The biodiesel yield increased with the increase in the methanol to oil ratio with 4:1 to 8:1 being the optimal range. But, increasing the ratio to 10:1 did not improve the yield because of phase separation and unreacted methanol. The yield and calorific value of the biodiesel was also influenced by the reaction temperature where moderate temperature of 50-55°C was ideal for transesterification.

Low temperatures led to low reaction rates and low conversion levels while high temperatures might lead to thermal degradation and side reactions. Reaction time also had an impact on yield where longer times of 90-120 minutes allowed for all the triglycerides to be esterified while shorter times produced lower yields due to the presence of unreacted triglycerides. Another factor was the catalyst concentration where 1- 1.5% w/w showed to be effective in increasing biodiesel production due to increased reaction rates. Lesser concentration of the catalyst reduced the reaction rate while 2% concentration of the catalyst formed soap which decreases yield and biodiesel purity. In conclusion, the findings reveal that biodiesel yield is highest under conditions of moderate methanol to oil ratio, reaction temperature, reaction time and catalyst concentration. Nevertheless, calorific value is not significantly affected by the process conditions and it can be inferred that the post-reaction purification steps may have a larger impact on the fuel energy content.

III.2 ANOVA ANALYSIS

The ANOVA analysis of biodiesel yield and calorific value, as shown in Table 4 and 5, gives a quantitative assessment of the effects of the transesterification parameters, namely, methanol to oil ratio, reaction temperature, reaction time and catalyst concentration on the output responses. In terms of biodiesel yield, it was observed that none of the parameters had any significant effect at a 0.05 level of significance. The methanol-to-oil ratio with a p value of 0.2015, the reaction temperature with a p value of 0.1067, the reaction time with a p value of 0.9222 and the catalyst concentration with a p value of 0.5338 were all greater than 0.05 and therefore, their effects on the yield can be considered non-significant within the range of the experiments. Nonetheless, the p-value of reaction temperature is lower than that of other factors, which indicates that it has a more significant but not very significant impact on yield, which may be attributed to its positive effect on the kinetic of transesterification and ester formation.

Table 4. ANOVA Results for Biodiesel Yield (%)

Source	Sum of Squares	Degrees of Freedom (DF)	F-value	P-value
Methanol-to-Oil Ratio	186.18	3	1.96	0.2015
Reaction Temperature (°C)	241.06	3	2.54	0.1067
Reaction Time (Minutes)	8.55	3	0.09	0.9222
Catalyst Concentration (% w/w)	53.51	3	0.56	0.5338
Residual	285.24	3		
Total	774.55	15		

Source: Authors, (2026).

On the other hand, the ANOVA of the calorific value showed that reaction temperature has a p-value of 0.0173 and F-value of 7.8644, which means that the calorific value is sensitive to temperature changes. This is technically valid since the reaction temperature impacts the energy level of the methyl ester formed, the purity and the molecular composition of biodiesel. The reaction temperature has an inverse relationship with the amount of residual unreacted triglycerides and a direct relationship with the energy content of biodiesel; where a higher reaction temperature produces biodiesel with higher energy content. On the other hand, methanol-to-oil ratio (p = 0.6849), reaction time (p = 0.4167), and catalyst concentration (p = 0.2999) were not significant for calorific value, which indicates

that the fuel energy content is not as sensitive to these parameters as temperature. As in Table 4 and Table 5, the analysis of variance indicates that reaction temperature is a significant factor to biodiesel quality, especially the calorific value while biodiesel yield is a function of all the parameters as a whole rather than the individual parameter.

III.3 OPTIMIZATION RESULTS

The biodiesel yield and calorific value of the biodiesel produced from the WSM optimization results are presented in the Table 6 to determine the effect of the transesterification parameters and the most suitable experimental run. The maximum WSM value of 0.9957 was obtained in Run 10 which has biodiesel yield of 96.15% and calorific value of 39.67 MJ/kg; therefore, it can be concluded that the selected process conditions provided the maximum biodiesel production with high fuel quality. This indicates that the concentration of methanol to oil should be 8:1, reaction temperature of 50°C, reaction time 120 minutes and 1.5% catalyst concentration as the best conditions for high conversion efficiency and energy content. On the other hand, the ANOVA of the calorific value showed that reaction temperature has a p-value of 0.0173 and F-value of 7.8644, which means that the calorific value is sensitive to temperature changes.

This is technically valid since the reaction temperature impacts the energy level of the methyl ester formed, the purity and the molecular composition of biodiesel. The reaction temperature has an inverse relationship with the amount of residual unreacted triglycerides and a direct relationship with the energy content of biodiesel; where a higher reaction temperature produces biodiesel with higher energy content. On the other hand, methanol-to-oil ratio ($p = 0.6849$), reaction time ($p = 0.4167$), and catalyst concentration ($p = 0.2999$) were not significant for calorific value, which indicates that the fuel energy content is not as sensitive to these parameters as temperature. As in Table 4 and Table 5, the analysis of variance indicates that reaction temperature is a significant factor to biodiesel quality, especially the calorific value while biodiesel yield is a function of all the parameters as a whole rather than the individual parameter.

Table 6: Weighted sum optimization results.

Run	Yield (%)	CV	Yield _{norm}	CV _{norm}	WSM score	Rank
1	72.44	38.92	0.753406136	0.9705736	0.84027311	16
2	84	39.19	0.873634945	0.9773067	0.91510366	12
3	91.63	39.59	0.95299012	0.9872818	0.96670679	2
4	75.29	39.4	0.783047322	0.9825436	0.86284585	15
5	91.89	39.22	0.955694228	0.9780549	0.96463848	3
6	79.54	39.38	0.82724909	0.9820449	0.88916741	14
7	84.46	39.56	0.878419137	0.9865337	0.92166495	10
8	90.86	39.76	0.944981799	0.9915212	0.96359756	4
9	85.1	39.38	0.885075403	0.9820449	0.9238632	9
10	96.15	39.67	1	0.9892768	0.99571072	1
11	88.81	40.1	0.923660946	1	0.95419657	6
12	82.52	39.61	0.85824233	0.9877805	0.91005762	13
13	89.07	39.45	0.926365055	0.9837905	0.94933524	7
14	84.79	39.22	0.881851274	0.9780549	0.92033271	11
15	90.73	39.72	0.943629745	0.9905237	0.96238732	5
16	85.45	39.68	0.888715549	0.9895262	0.9290398	8

Source: Authors, (2026).

Runs 3, 5, and 8 also had high WSM scores of 0.9667, 0.9646, and 0.9636 respectively, which means that even if there is a slight change in the concentration of the catalyst and the reaction time within the range of 1.0 – 1.5% for the catalyst and 90 – 120 minutes for the reaction time, the yield of biodiesel is still high and the energy content is not significantly affected. The optimal reaction temperature was found to be around 50–55°C, which was evident from the higher ranked runs, as moderate temperature favors the conversion of triglycerides to methyl esters without causing degradation of the latter. On the other hand, the least WSM score of 0.8402 was obtained in Run 1 which produced the least biodiesel yield of 72.44% and calorific value of 38.92 MJ/kg. This implies that the methanol-to-oil ratio of 4:1, reaction temperature of 45°C, reaction time of 30 minutes and the catalyst concentration of 0.5% were not efficient for transesterification. The lower catalyst concentration and shorter reaction time contributed to poor esterification thus yielding lower biodiesel and energy content due to unreacted triglycerides and presence of impurities. The values of calorific values were within a small range of 38.92–40.1 MJ/kg and the highest CV of 40.1 MJ/kg was recorded in Run 11 where reaction temperature was 55°C and catalyst concentration was 1.0%. This means that high reaction temperatures increase fuel energy density probably as a result of increased esterification and low residual impurities. However, the maximum biodiesel yield does not always mean the maximum CV, which suggests that biodiesel quality depends not only on yield, but the FAME profile and purity as well.

III.4 CONFIRMATION OF OPTIMAL CONDITIONS

The confirmation experiments were also carried out using the optimal conditions of methanol to oil ratio of 8:1, reaction temperature of 55°C, reaction time of 120 minutes and catalyst concentration of 1.5%. The results of the confirmation experiments are presented in Table 7 below. The three trials gave biodiesel production of 96.08%, 96.22%, and 96.18% with calorific values of 39.62, 39.75, and 39.72 MJ/kg respectively. The biodiesel yield was found to be $96.16 \pm 0.07\%$ and the calorific value 39.70 ± 0.08 MJ/kg, which reveals that there was high degree of precision and reliability at the identified optimal conditions.

Table 7. Confirmation test results at optimal conditions

Test Run	Methanol-to-Oil Ratio	Reaction Temperature (°C)	Reaction Time (min)	Catalyst Concentration (% w/w)	Biodiesel Yield (%)	Calorific Value (MJ/kg)
Confirmation Run 1	08:01	55	120	1.5	96.08	39.62
Confirmation Run 2	08:01	55	120	1.5	96.22	39.75
Confirmation Run 3	08:01	55	120	1.5	96.18	39.72
Average	—	—	—	—	96.16	39.70

Source: Authors, (2026).

In comparison to the Experimental Run 10 which was earlier considered optimal according to WSM scoring and gave biodiesel yield of 96.15% and calorific value of 39.67 MJ/kg, the confirmation results are quite similar. This good correlation further supports the effectiveness and efficiency of the optimization framework to guarantee that the chosen process conditions not only yield the highest biodiesel concentration but also biodiesel with high energy density. A small standard deviation across the runs also underlines the robustness of the transesterification process under these optimized conditions, which supports the applicability of these conditions for large-scale biodiesel production from mango seed kernel oil.

IV. CONCLUSION

This study describes the efficient process of biodiesel production from mango seed kernel oil through a multiple parameter transesterification process. The factors such as methanol to oil ratio, reaction temperature, reaction time and catalyst concentration were optimized using Taguchi L16 orthogonal array and biodiesel yield and calorific value were taken as the response characteristics. The WSM was used for the multi-objective optimization, which aimed at achieving the optimal production rate and the quality of the fuel.

- The optimal conditions were found to be a methanol to oil ratio of 8:1, the temperature of 55°C, the time of 120 minutes and the concentration of the catalyst of 1.5% w/w. Under these conditions, the process gave the highest biodiesel conversion efficiency of 96.15% and calorific value of 39.67 MJ/kg.
- To confirm the reliability of the optimized settings, confirmation experiments were carried out thrice and the average biodiesel yield obtained was $96.16 \pm 0.07\%$ and average calorific value of the biodiesel produced was 39.70 ± 0.08 MJ/kg which proves the repeatability and robustness of the process.
- The ANOVA test showed that among all the studied parameters, reaction temperature had a significant effect on calorific value of the biodiesel at $p < 0.05$, whereas the effect of reaction temperature on the yield was significant at the practical level but insignificant at the 95% confidence level. It was also observed that the yield is more sensitive to the joint and cumulative effect of all the parameters rather than the individual one.

The findings of this study support the use of mango seed kernel oil as a viable non-food source for biodiesel production. The enhanced transesterification process, as confirmed by statistical and experimental methods, provides high biodiesel conversion rate and stable fuel quality, which can be suitable for further scale-up and practical biofuel production. The further studies may involve the investigation of engine characteristics, emissions, and life cycle assessment of mango seed biodiesel and the application of optimization and machine learning for the improvement of the process and its application.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Popat Gunjal, Vijaykumar Pandey.

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Investigation: Popat Gunjal, Vijaykumar Pandey.

Discussion of results: Popat Gunjal, Vijaykumar Pandey.

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