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Research Article

Optimized conversion of waste vegetable oil to biofuel with Meta heuristic methods and design of experiments

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Abstract. Biodiesel generated from waste cooking oil (WCO) shows enormous potential for accomplishing SDGs and embracing circular economy principles. This strategy coincides with SDGs 7 and 12, which promote clean energy along with ethical consumerism, by converting waste cooking oil into biofuel. It reduces dependency on fossil fuels, reduces emissions, and promotes sustainable energy sources. Furthermore, using WCO biodiesel adheres to the circular economy concept, reducing waste and pollution while conserving resources (SDGs 12, 14, and 15). To optimize this process, a hybrid technique comprising RSM, ANOVA, and particle swarm optimization is being explored. Researchers achieved 90% biodiesel production employing this technology, encouraging both eco-friendly energy and resource-efficient practices. The optimized parameters produced remarkable results: 82.98% biodiesel generation with a reaction time of 101 minutes, 2% catalyst, and a methanol-to-oil ratio of 20%, demonstrating the potential of this integrated strategy.

Keywords: Biofuels; optimization; alternative fuel; meta-heuristic optimization; sustainability.

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1. Introduction

Biodiesel made from waste cooking oil (WCO) is a crucial response that could make a big difference for both the Sustainable Development Goals (SDGs) and the tenets of a circular economy. Employing WCO to make biofuel has a double benefit, especially since the world is facing ecological issues. First of all, it fits with the SDGs about clean energy (SDG 7) and ethical production and usage (SDG 12) (Mulligan et al., 2020)(Yu et al., 2022). By turning used cooking oil into a useful energy source, this method lowers the need for fossil fuels and cuts down on greenhouse gas emissions, resulting in easy-to-use cleaner, more sustainable energy sources. Additionally, employing biodiesel made from WCO is an unambiguous form of the circular economy, that encourages the efficient use of resources (SDG 12) and reduces waste and pollution (SDGs 14 and 15). This method not only helps keep the environment cleaner by recycling and reusing used cooking oil, but it also helps protect natural resources and communities. This input is in line with SDGs that focus on life in the ocean and on life on land, and it shows how important it is to protect both environments (Beccarello & Di Foggia, 2022)(Cozzi et al., 2022).

Furthermore, using WCO to make biodiesel contributes to growth in the economy and decent work (SDG 8) by giving local businesses a chance to help with collection, conversion, and dissemination. It drives users to come up with new ideas and put money into sustainable technologies. This renders the economy more stable and helps people find jobs in the area. This positive cycle helps with community growth, which is one of the main goals of the SDGs. Hence, the role of biodiesel produced from used cooking oil goes far beyond its energy benefits. It shows how innovation in sustainability adheres to can help society, the economy, and the environment work together better. It does this by aligning with the ideals of the circular economy and addressing key SDGs. As countries try to find global answers to problems, the use of biodiesel made from WCO products is a big step toward a more sustainable and fair future (Hosseinzadeh-Bandbafha et al., 2022)(Mulligan et al., 2020)(Zhao et al., 2021).

There have been sincere efforts by researchers to synthesize the biodiesel from WCO. Khan et al. (Mahmood Khan et al., 2020) employed a catalyst derived from ostrich bone for synthesizing the biodiesel from WCO. It indicates that hydroxyapatite produced from ostrich bones shows excellent catalytic performance in the production of biodiesel from WCO. The synthesized catalyst maintained acceptable catalytic activity despite being recycled a total of four times, implying low-cost biodiesel manufacturing prospects. Jume et al. (Jume et al., 2020) employed graphene oxide doped metallic oxide as a catalyst for biodiesel synthesis from WCO. The effects of oil-to-alcohol ratio, reaction duration, and temperature of reaction on the transesterification FAME production were investigated. According to the data, the greatest FAMEs yield of 91% was achieved under a setting of 1:0.5 (w/w) GO: ZrO2-SrO material ratio, reaction duration of 90 minutes, oil to methanol ratio (1:4), and temperature of 120 °C. As a result, our work demonstrated that GO@ZrO2-SrO may be employed as a viable heterogeneous catalyst for the production of biodiesel from WCO.

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Several other researchers have investigated biodiesel synthesis from WCO using a catalyst (El-Gendy et al., 2016)(Falowo et al., 2021)(Jayaraman et al., 2022)(Sulaiman et al., 2021).

Optimizing the efficiency and economic feasibility of biodiesel production is important. WCO content can vary significantly, influencing biodiesel production and quality. As a consequence, optimizing the synthesis process provides unchanged and excellent biodiesel output while reducing waste and resource usage. In addition, as the need for sources of clean energy grows, optimized biodiesel production helps to achieve energy security and reduce reliance on fossil fuels (Degfie et al., 2019). The contribution of Response Surface Methodology (RSM) and metaheuristic approaches in attaining this optimization is critical. RSM is a statistical approach used for studying the effect of numerous factors on a response, in this instance, biodiesel yield and quality. RSM allows us to determine the ideal conditions for biodiesel synthesis by performing experiments and modeling the link between input factors and output responses. This approach helps to reduce the number of experimental trials, save time and money, and reduce trial and error (Moyo et al., 2021).

Metaheuristic approaches, on the one hand, are sophisticated optimization algorithms inspired by natural processes like the theory of evolution, swarm intelligence, and simulated annealing. These methods search enormous solution spaces for optimum or near-optimal answers that standard techniques may miss. Considering the complexities of biodiesel synthesizing, metaheuristic approaches provide a larger search capacity by taking into account several parameters and their interactions. Genetic Algorithms, Particle Swarm Optimisation, and Simulated Annealing are examples of algorithms that can effectively explore the complex parameter space to identify optimal conditions for biodiesel synthesis (Azad et al., 2020)(Houssein et al., 2022). The incorporation of RSM and metaheuristic approaches in biodiesel synthesis optimization not only speeds up the finding of optimal parameters for the process but also improves process comprehension. These strategies allow us to fine-tune the manufacturing process by taking into account various variables and interactions, therefore enhancing yield, quality, and overall process efficiency. As the world moves towards more sustainable energy practices, the use of these modern processes in biodiesel synthesis from waste cooking oil can make a substantial contribution to a greener and more sustainable future.

Given the foregoing, it is critical to create an intelligent hybrid method to optimize the biodiesel manufacturing process to minimize waste while increasing biodiesel yield. A hybrid strategy combining RSM-based design of experiments, ANOVA, and Meta heuristic approaches is explored in this work.

2. Methods and materials

2.1. Feedstock and other materials

The waste frying oil was obtained from the local restaurants and eateries in Delhi, India. Analytical reagent-grade chemicals including KOH, sulphuric acid, and Methyl alcohol were procured from an industrial chemical supplier. The collected waste oil was kept in containers so that mixed food particles and other impurities settled down due to gravity. It was then heated at 100 °C to remove impurities and water content, respectively. The FFA concentration was found to be 3.6%, hence two-stage transesterification was employed. The well-established and standardized process of biodiesel production from WCO using KOH and methanol was used (Hariram et al., 2021)(Wong et al., 2023). The physicochemical properties of produced biodiesel are appended below in **Table 1**.

Table 1. Test biodiesel properties

Name of biodiesel property	Test standard (ASTM)	WCO	WCO biodiesel
Specific gravity	D1298	0.926	0.898
Cloud point	D93	15 °C	7 °C
Cetane number	D613	--	51
Flash point	D2500	238 °C	156 °C
LCV	D2015	36550 (kJ/kg)	38500 (kJ/kg)

2.2. Design of Experiments

In the present study, the Box-Behnken design was employed for the design of the experiment. The adoption of the Box-Behnken design plays an important role in maximizing the production of biodiesel from WCO. This design technique is particularly helpful when dealing with the complex interaction of various factors inherent in biodiesel manufacturing processes. Diverse variables involved in biodiesel syntheses, like catalyst concentration, methanol-to-oil ratio, and reaction duration, all have an impact on both the yield and quality of the biodiesel product. The Box-Behnken design provides a systematic technique for assessing these aspects thoroughly, thereby reducing the number of experimental trials necessary (Ramachander et al., 2021). This design not only streamlines the process but also uncovers crucial insights by specifically choosing experimental circumstances, often at three levels.

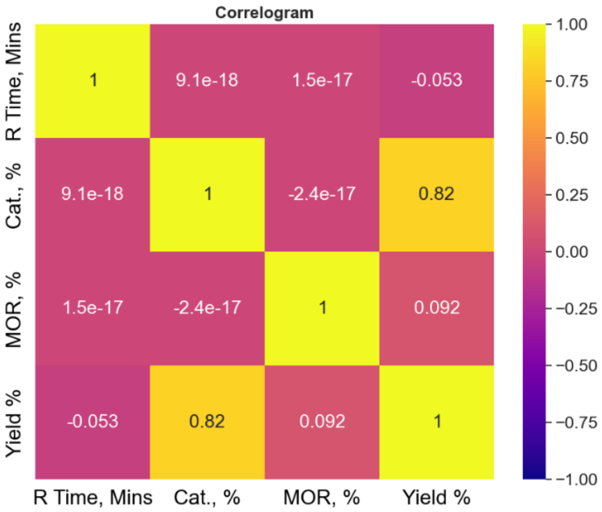


Figure 1. Correlation matrix for the data

One of its key advantages is its capacity to explore the challenging connections between factors. Biodiesel production is seldom influenced by individual elements; rather, it is the relationships that are important. The integration of studies at several factor levels in the Box-Behnken design helps the detection of synergistic or antagonistic effects that would otherwise be hidden in a typical single-factor analysis. Furthermore, the Box-Behnken architecture makes it feasible to forecast ideal conditions for biodiesel synthesis. Researchers can envision the precise conditions that contribute to maximum production or quality by building a second-degree polynomial regression model based on experimental data. This model incorporates linear, quadratic, and interaction effects, providing an entire overview of the parameter landscape. The BBD-based design matrix is presented in **Table 2**. The data thus collected was used for the development of a correlation matrix as depicted in **Figure 1**. It can be observed that a catalyst with a correlation value of 0.82 is the major factor in influencing the biodiesel yield.

Table 2 Design matrix based on Box-Behnken design

Exp. Run	Catalyst Conc., %	Reaction time, mins.	M/O ratio	Yield, %
1	1.00	60.00	40.00	25.23
11	2.00	60.00	60.00	79.28
9	2.00	60.00	20.00	79.7
2	3.00	60.00	40.00	73.44
7	1.00	120.00	60.00	48.19
5	1.00	120.00	20.00	23.9
13	2.00	120.00	40.00	80.11
16	2.00	120.00	40.00	80.12
14	2.00	120.00	40.00	80.11
17	2.00	120.00	40.00	80.13
15	2.00	120.00	40.00	80.11
8	3.00	120.00	60.00	78.65
6	3.00	120.00	20.00	90.28
3	1.00	180.00	40.00	20.6
12	2.00	180.00	60.00	81.57
10	2.00	180.00	20.00	70.11
4	3.00	180.00	40.00	71.51

2.3. Analysis of variance

ANOVA (analysis of variance) was employed to analyze the data. Analysis of Variance (ANOVA) shows up as a helpful statistical technique in the context of optimizing the production of biodiesel from WCO. ANOVA enables an in-depth assessment of the effects of many variables on biodiesel output and quality. ANOVA assists in finding the most significant factors in the synthesis process by examining the causes of variation and measuring their contributions. This knowledge is critical for making educated decisions regarding which parameters to prioritize to achieve desired biodiesel qualities (Dimitriou et al., 2013). The capacity of ANOVA to analyze both individual and interacting impacts of components improves our knowledge of the complex linkages that drive biodiesel production, resulting in improved and environmentally friendly procedures. The outcome of ANOVA is presented in **Table 3**.

Table 3. ANOVA of the data

Source	Mean Square	Value “F”	p-value (Prob > F)	
Model	915.6444	6124.01	< 0.0001	noteworthy
A (Cat.)	4800.04	32103.61	< 0.0001	
B (RT)	24.01245	160.6	< 0.0001	
C (MOR)	70.21125	469.5866	< 0.0001	
AB	1.8225	12.18924	0.0101	
AC	322.5616	2157.355	< 0.0001	
BC	35.2836	235.9836	< 0.0001	
A^2	2613.82	17481.74	< 0.0001	
B^2	237.1896	1586.371	< 0.0001	
C^2	107.5704	719.452	< 0.0001	
Residual	0.149517			
Lack of Fit	0.348767	4359.583	< 0.0001	noteworthy

The findings from the ANOVA offer insight into the optimization method for biodiesel synthesis from discarded cooking oil. The importance of numerous factors and their interactions in impacting biodiesel production and quality is shown by the "F" test statistic and accompanying p-values. The model's overall efficacy is demonstrated by the F-value of 6124.01, which is much lower than its minimum value of 0.0001, indicating its strong dependability. Individual contributions of categorical variables A (Cat.), reaction time (RT), and methanol-to-oil ratio (MOR) are all demonstrated to be very significant with p-values of 0.0001. Furthermore, the interaction variables AB, AC, and BC, as well as the quadratic terms A2, B2, and C2, all have a significant impact on the response variable, as evidenced by their low p-values. The presence of residual error is also highlighted in the ANOVA table, indicating that the model does not capture all variability. The Lack of Fit test emphasizes the importance of modifying the model to better anticipate biodiesel properties. Overall, the ANOVA results assist in the identification of crucial components and interactions, laying the groundwork for optimizing the biodiesel synthesis procedure.

2.4. Particle swarm optimization

Particle Swarm Optimisation (PSO) is a robust metaheuristic method that can help a lot with optimizing the method of making biodiesel from WCO. PSO is based on how birds or fish act as a group and try to find the best solution by changing a swarm of possible solutions repeatedly and yet again (Bahiraei et al., 2021)(Chen et al., 2020). In this situation, PSO can help fine-tune the process factors, like catalyst concentration, reaction time, and the ratio of methanol to oil, to get the best biodiesel quality and yield. PSO can quickly find the best answer by efficiently exploring the parameter space and adapting the swarm's movement based on how well each individual is performing. This method is especially useful for resolving the "Lack of Fit" that was found in the ANOVA. This makes it possible to predict biodiesel properties more accurately and improve the optimization process. Overall, Particle Swarm Optimisation can add to the statistical knowledge learned from ANOVA and make the optimization of making biodiesel from used cooking oil work better.

3. Results and discussion

3.1. Model-prediction

The ANOVA helped in the development of a mathematical model for biodiesel yield as given in Eq. (1).

$$\begin{aligned}\text{Yield} = {} & -102.14 + 140.77 * \text{Cat.} + 0.35 * \text{RT} - 0.262 * \text{MOR} + 0.0113 * \text{Cat.}* \\ & \text{RT} - 0.45 * \text{Cat.}* \text{MOR} + 0.0025 * \text{RT} * \text{MOR} - 24.9 * \text{Cat.}* \text{Cat} - 0.002 * \\ & \text{RT} * \text{RT} + 0.013 * \text{MOR} * \text{MOR} \qquad \text{Eq. (1)}\end{aligned}$$

The model was employed to predict the values at input parameter settings. **Figure 2** depicts a comparative graph between actual and model-predicted biodiesel yield values.

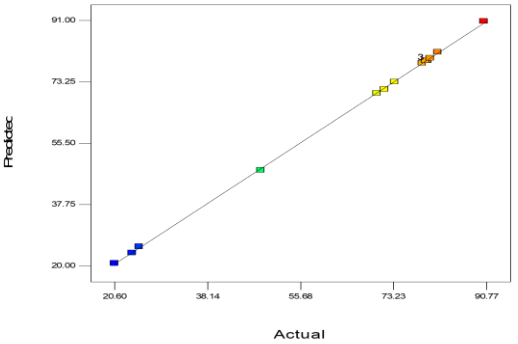
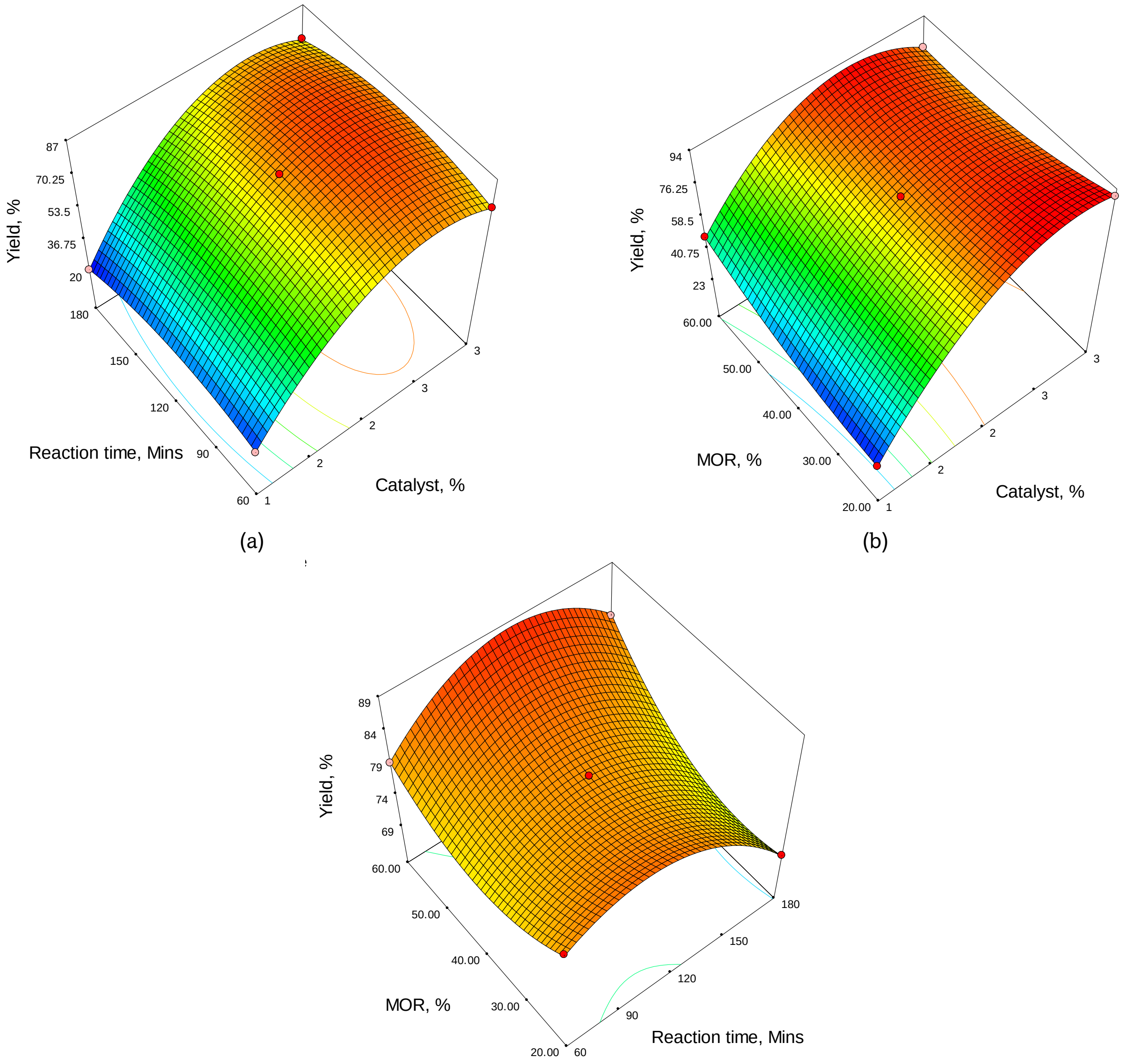


Figure 2. Model forecasted vs. actual biodiesel yield in %

3.2. RSM-based analysis

The 3-D surface diagrams were developed to reveal the effects of various control factors on the response variable (biodiesel yield %).



(a) (b)

(c)

Figure 3. Response surface depicting the effects of
(a) reaction time and catalyst %; (b) catalyst % and methanol to oil ratio; (c) methanol to oil ratio and reaction time on biodiesel yield

The combined and interactive effect of catalyst concentration and time of reaction is depicted in **Figure 3 (a)**. The surface diagram corroborates the results shown in ANOVA results as well as the correlogram since the catalyst concentration shows the highest effect on biodiesel yield. On the other side, the effect of reaction time was not so prominent. It initially increases but then decreases again. In the case of methanol to oil ratio and catalyst concentration again the catalyst % shows the highest effect on biodiesel yield, as depicted in **Figure 3(c)**. The highest biodiesel yield to the tune of 90% when 2.5% catalyst and 20% methanol to oil was employed. While the effects of methanol to oil ratio and reaction time on biodiesel yield were compared in **Figure 3(c)**, it was observed that both M/O ratio and reaction time have varying effects on biodiesel yield. The peak biodiesel yield was observed at 60% methanol to oil ratio and 2 hours reaction time.

3.3. PSO based optimization

The surface diagram and experimental observation reveal that a trade-off analysis is needed to find out the best operating setting at which maximum biodiesel may be produced using minimum resources. In the case of producing biodiesel from food waste-based cooling oil, PSO works by simulating a swarm of particles that are looking for potential solutions. The position of each particle in the search space is related to a certain set of process factors, such as the temperature of the reaction, the concentration of the catalyst, and the molar ratio. As the optimization process moves on, particles change their positions based on what they know and what the best answer is that the whole swarm has found. This way of working collectively makes sure that the swarm ends up in good parts of the parameter space. PSO dynamically balances exploration and exploitation by constantly updating particle coordinates using velocity vectors. This lets it explore a wide range of parameter combos quickly while focusing on the best ones.

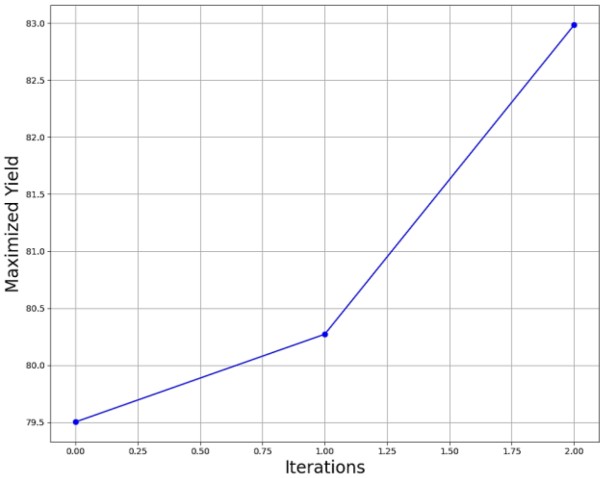


Figure 4. PSO iterations

In the case of biodiesel synthesis, PSO can try out different parameter pairs to find the best ones that lead to the highest yield. For example, it can figure out the best combination of MOR, RT, and catalyst % for achieving the most effective conversion. By changing these factors and looking at how they affect the amount of biodiesel made, PSO can find the best set of conditions. PSO is also efficient at solving nonlinear and multidimensional optimization problems. This makes it a great tool for optimizing biodiesel synthesis since it involves a lot of complicated interactions between different process factors. PSO is a useful tool for improving the biodiesel yield from used cooking oil because it can rapidly explore the parameter space, adapt to altering conditions, and converge on optimal solutions. This contributes to making energy production more sustainable and reduces waste. **Figure 4** depicts the iterations and converging during PSO-based optimization. The beats operating setting achieved using PSO were 101 mins reaction time, 2% catalyst, and 20% methanol to oil ratio producing 82.98% biodiesel.

4. Conclusion

WCO-derived biodiesel holds enormous promise for environmentally friendly energy production as well as waste reduction. A hybrid optimization strategy integrating Response Surface Methodology (RSM), Analysis of Variance (ANOVA), and Particle Swarm Optimisation (PSO) is investigated in this work to improve biodiesel yield from WCO. The hybrid optimization approach, which combines RSM, ANOVA, and PSO, efficiently optimizes biodiesel production. RSM and ANOVA uncover key variables influencing biodiesel yield, with catalyst concentration (p 0.0001) and reaction time (p 0.0001) demonstrating this. PSO improves yield even further by identifying optimal parameter ratios such as 2% catalyst, 20% methanol-to-oil ratio, and 101 minutes reaction time, yielding 82.98% biodiesel.

Given the intricate interactions among parameters and biodiesel yield, advanced optimization approaches are employed. RSM and ANOVA reveal relevant factors and interactions, whereas PSO efficiently navigates the multidimensional parameter space, convergent on optimal solutions. The hybrid strategy illustrates its ability to be implemented across multiple sectors, promoting a greener future. It offers useful insights for optimizing processes, decreasing waste, and improving sustainability in areas other than biodiesel synthesis. In essence, the hybrid optimization technique is a critical tool for unlocking the potential of WCO-derived biodiesel, assuring a more sustainable energy future while advancing circular economy goals.

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