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A Comparison of Iron and Aluminum Electrodes in Electric-Field-Enhanced Biodiesel Production

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Abstract –*This study investigates biodiesel production under applied electric fields using two common, cost-effective electrode materials—iron and aluminum—operated under identical conditions. Used palm oil was transesterified with methanol at a molar ratio of 5:1. The temperature was 40 °C for 2 minutes, with sodium hydroxide (0.5–0.7% w/w) as the catalyst and electric field intensities of 80–240 V. A 3^2 factorial design within Response Surface Methodology (RSM) was used to quantify individual and interaction effects and to identify optimal conditions. The highest yield with iron electrodes was 81.12% at 0.5% NaOH and 125 V; for aluminum, the maximum yield was 80.12% at 0.6% NaOH and 138 V. Iron required lower field strength and catalyst loading, consistent with better chemical stability in alkaline media. These results clarify how electrode material affects yield and separation performance in electric-field-assisted biodiesel production and inform material selection for cost-effective, energy-efficient process design.*

Keywords –Biodiesel, electric field, electrode materials, response surface methodology, transesterification.

1. INTRODUCTION

The global pursuit of sustainable and renewable energy sources is driven by two critical factors: the depletion of finite fossil fuel resources and the severe environmental consequences of their combustion, particularly the escalation of greenhouse gas emissions. Biodiesel, a biodegradable and non-toxic biofuel, represents a viable substitute for conventional diesel fuel. It can be produced from diverse biological materials, such as vegetable oils, animal fats, and used cooking oil, through four primary methods: direct blended, micro-emulsion, thermal cracking, and transesterification [1]. However, transesterification is the most employed industrial method.

Optimizing the transesterification process to improve yield and reduce costs has been the focus of extensive research. Response Surface Methodology (RSM) offers an effective set of statistical tools for modeling and analyzing the relationship between multiple process variables and their resulting output, making it ideal for optimization studies. For example, the optimization of biodiesel production from Lagenaria siceraria seed oil using RSM was investigated by Fakai *et al*. [4]. It was concluded in their study that the highest yield could be obtained at a molar ratio of 9.07:1, a reaction time of 70.59 minutes, a temperature of 53.09 °C, and a catalyst concentration of 0.88%. Other studies by Angassa *et al*. [5], Mohadesi *et al*. [6], and Yamin *et al*. [7] have similarly utilized RSM to optimize production from various feedstocks, including castor oil and waste cooking oil, by investigating key variables such as oil to methanol ratio, catalyst concentration, reaction time, and temperature.

In addition to traditional optimization, advanced process intensification techniques have been explored. Microwave-assisted technology, for instance, has been shown to drastically shorten production time [2]. Another promising approach involves the application of an electric field. This concept is partly based on the finding by Wang *et al*. [8] that electric field intensity (EFI) can reduce the viscosity of fluids, thereby potentially enhancing mass transfer and reaction kinetics. The work by Wang *et al*. [8] indicated that electric field intensity (EFI) can reduce fluid viscosity, a principle subsequently applied in various investigations [9]-[10]. Sangsawang and Phetsuwan [11] used electric fields to produce biodiesel from animal fat. Sangsawang *et al*. [12] successfully applied electric fields to the transesterification of animal fat and refined palm olein oil, reporting that an electric fields intensity of 85 V/cm for 2 minutes yielded 98.41% biodiesel.

The field of electrocatalytic transesterification further reveals that the reaction can occur at ambient temperatures and that the choice of electrode material and configuration significantly impacts performance [13]. Ampairojanawong *et al*. [14] investigated five different electrode configurations, concluding that a point-to-point setup achieved the highest yield, highlighting the critical role of the electrode design.

Previous research has successfully demonstrated the potential of electric fields to intensify the biodiesel production process. However, the investigation has predominantly focused on parameters like field intensity, application time, and electrode geometry. A significant research gap persists regarding the comparative performance of different, readily available, and low-cost electrode materials. The selection of electrode material could have a substantial impact on

DOI: https://doi.org/10.64289/iej.25.03A11.1005289

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both the catalytic activity and the overall economic feasibility of the process.

The performance of two common, low-cost metals, iron (Fe) and aluminum (Al), when utilized as electrodes in biodiesel production is therefore systematically evaluated in this work. To address the aforementioned gap in the literature, both materials were tested under an identical set of experimental conditions to allow for a direct comparison. The primary objective is to identify and compare the optimal production conditions for each electrode material using Response Surface Methodology (RSM). This research will provide valuable insights into the selection of materials for designing efficient and cost-effective electrocatalytic reactors for biodiesel production.

2. MATERIALS AND METHODS

2.1 *Materials*

In this investigation, biodiesel was produced from the transesterification reaction between used vegetable oil and methanol. The reactants included methanol of 99.9% purity and sodium hydroxide (NaOH) as a homogeneous catalyst. NaOH was chosen for its practical advantages, namely its low cost and widespread availability. In accordance with findings from previous research [4]-[7], [9]-[11], the catalyst concentration was limited to a maximum of 1% by weight of the oil to mitigate the risk of soap formation and optimize the reaction.

2.2 *Experimental Setup and Procedure*

Experiments were conducted in a transparent glass reactor with point-to-point electrodes separated by 3 cm. A 200 V, 50 Hz power supply with a variable transformer provided electric field intensities of 80, 160, and 240 V. No mechanical stirring was used. The oil-to-methanol molar ratio was fixed at 5:1, the reaction temperature was 40 °C, and NaOH catalyst levels were 0.5%, 0.6%, and 0.7% by weight. The applied field duration was 2 minutes. The product mixture was maintained in a static condition for 120 minutes to perform the gravitational phase. The upper is biodiesel and the phase is glycerol. The biodiesel layer was subsequently purified through two washing cycles using water at 60 °C, followed by a drying step to remove residual moisture prior to analysis.

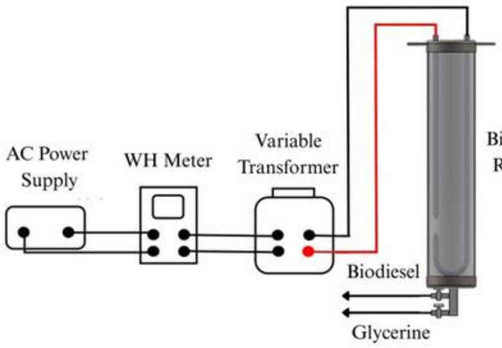

Fig. 1. Experiment apparatus.

In this study, the reaction was conducted without mechanical stirring. An electric field was instead employed to facilitate the mixing of reactants, a technique supported by the findings of Wang *et al.* [8] which show that electric fields can effectively lower fluid surface tension. The performance of this method was evaluated against a conventional reaction utilizing mechanical agitation.

For purification, the biodiesel product was washed twice with hot water (60°C). A subsequent drying step at 100°C for 10 minutes was performed to eliminate residual water before the final yield was calculated as per Equation (1)

$$\text{Yield }\% = \frac{\text{Weight of Biodiesel}}{\text{Weight of Palm Oil}} \times 100\% \qquad (1)$$

This experiment utilized a digital scale with two decimal places, and each experiment was weighed three times to ensure accuracy.

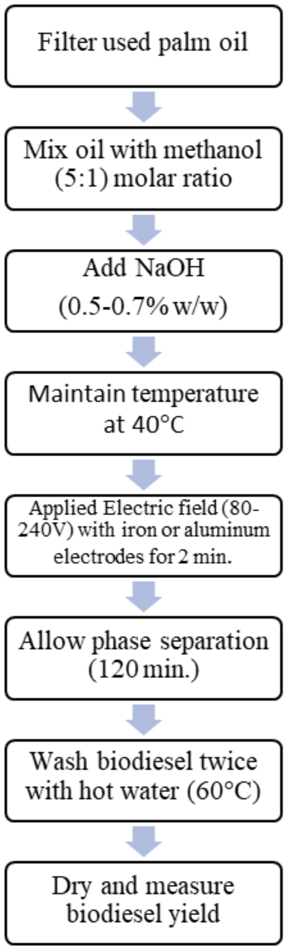

Fig. 2. Experiment procedure.

2.3 *Experimental Design and Data Analysis*

The design of experiment for biodiesel production in this study was based on Response Surface Method (RSM), considering two main factors: percentage of NaOH (%) and the electric field intensity (V).

The experiment followed a 3^2-factorial design, resulting in a total of 9 experiments. Each set of 9 experiments was conducted using both iron and aluminum electrodes. For statistical analysis, the experimental conditions were standardized by coding the factor levels as –1, 0, and +1 for low, medium and high levels. The variables were defined in Table 1.

Table 1. Levels and ranges of primary parameters.

Parameters	Factors	Level		
		-1	0	+1
NaOH (%)	X_1	0.5	0.6	0.7
EFI (V)	X_2	80	160	240

The study employs an orthogonal design, with the complete experimental matrix presented in Table 2. This matrix specifies the coded levels for the primary variables (X_1 and X_2) and their corresponding quadratic (X_1^2, X_2^2) and interaction (X_1X_2) terms. For all calculations, these coded levels are substituted with their actual experimental values as defined by Equation (2).

$$Y_i = \beta_0 + \sum_{i=1}^{N} \beta_i X_i + \sum_{i=1}^{N} \beta_{ii} X_i^2 + \sum_{i=1 i<j}^{N-1} \sum_{i=2}^{N} \beta_{ij} X_i X_j \quad (2)$$

where Y_i is the % yield from transesterification reaction, β_i, β_{ii}, and β_{ij} are the coefficients of the regression analysis and presented in Table 2 [12].

Table 2. Coefficients in Equation 2 and response vector (Y).

Run No.	β_0	X_1	X_2	X_1^2	X_2^2	X_1*X_2	Y_i
1	1	-1	-1	1/3	1/3	1	Y_1
2	1	0	-1	- 2/3	1/3	0	Y_2
3	1	1	-1	1/3	1/3	-1	Y_3
4	1	-1	0	1/3	1/3	0	Y_4
5	1	0	0	- 2/3	- 2/3	0	Y_5
6	1	1	0	1/3	- 2/3	0	Y_6
7	1	-1	1	1/3	- 2/3	-1	Y_7
8	1	0	1	- 2/3	1/3	0	Y_8
9	1	1	1	1/3	1/3	1	Y_9
10	1	1	1	1/3	1/3	1	Y_{10}
11	1	1	1	1/3	1/3	1	Y_{11}
12	1	1	1	1/3	1/3	1	Y_{12}
13	1	1	1	1/3	1/3	1	Y_{13}

where β_0 is shown in Equation (2). The constants of X_1 and X_2 which refer to Table 1 are the level of %NaOH and EFI. Y_i is the response vector, in this study, it means yield of production.

3. RESULTS AND DISCUSIONS

The experimental framework for this investigation was designed using Response Surface Methodology (RSM). Specifically, a Central Composite Design (CCD) with two independent variables at three levels was implemented for each electrode material (iron and aluminum). The design for each electrode comprised 13 experimental runs: 9 unique combinations and 5 replicates of the central point (run no. 9) to estimate the pure experimental error.

Consistent with prior research in biodiesel optimization [4]-[7], [12], a quadratic regression model was employed to analyze the relationship between the independent variables and the results. The calculated biodiesel yield (Y_i) was determined using this second-order polynomial model, which accounts for linear, quadratic, and interaction effects. The final predictive equations derived from the Analysis of Variance (ANOVA) are presented in Equations (3) for iron and (4) for aluminum.

3.1 Iron Electrodes

The statistical significance of the regression model for the iron electrode was validated through an analysis of variance (ANOVA), summarized in Table 3. The overall model proved to be highly significant (F-value = 28.92, P-value = 0.000), indicating a strong correlation with the experimental data. Further evaluation of the p-values identified the linear effects (X_1 and X_2), one quadratic effect (X_2^2), and the two-factor interaction (X_1X_2) as significant model components ($p < 0.05$). Consequently, a model reduction was performed by omitting the insignificant terms, yielding the refined empirical model expressed in Equation. (3).

$$Y = 84.16 - 5.6X_1 - 0.0126X_2 - 0.000174X_2^2 + 0.1118X_1X_2 \quad (3)$$

Table 3. Analysis of variance (ANOVA) of Equation 3 with iron electrodes.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	7.8300	1.5660	28.92	0.000
Linear	2	0.2513	0.1256	2.32	0.169
NaOH (X_1)	1	0.1960	0.1961	3.62	0.099*
EFI (X_2)	1	0.0552	0.0552	1.02	0.346*
Square	2	4.3764	2.1882	40.42	0.000
NaOH*NaOH (X_1=*X_1)	1	0.0381	0.0382	0.71	0.429*
EFI*EFI (X_2*X_2)	1	3.4275	3.4275	63.31	0.000
2-Way Interaction	1	3.2023	3.2023	59.15	0.000
NaOH*EFI (X_1*X_2)	1	3.2023	3.2023	59.15	0.000
Error	7	0.3790	0.0544		
Lack-of-Fit	3	0.3790	0.1263		
Pure Error	4	0	0		
Total	12	8.2091			

*Not-significant, P-Value > 0.05

3.2 Aluminum Electrodes

Table 4 summarizes the ANOVA for the quadratic model corresponding to the aluminum electrode system. The model's F-value of 4.13 and associated p-value of 0.046 establish its statistical significance at the 95% confidence level. Moreover, the model exhibited a non-significant Lack of Fit ($p > 0.05$), which validates its suitability and confirms that it is a robust representation of the experimental data.

An analysis of the individual regression coefficients in Table 4 reveals that only the quadratic term, X_2^2, had a statistically significant effect on the biodiesel yield ($p < 0.05$). The linear terms X_1 (% catalyst) and X_2 (EFI), despite having p-values greater than 0.05, were compulsorily included in the final model. These factors are essential to the study and should be preserved to uphold the hierarchical structure of the polynomial model. Therefore, after eliminating the non-significant interaction and other quadratic terms, the refined empirical relationship between the process parameters and biodiesel yield is expressed by Equation (4).

$$Y = 52.7 + 80.2X_1 + 0.0465X_2 + 0.00119X_2^2 \quad (4)$$

3.3 Model Validation

Figure 3 illustrates the percentage yields obtained from both the experiments and the predictions based on Equation (2), represented by scattered points. The solid line represents the line of best fit. The figure demonstrates that the model effectively captures the experimental data, as most of the points lie close to the best-fit line.

Table 4 Analysis of variance (ANOVA) of Equation 4 with Aluminum electrodes.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	5.4394	1.0879	4.13	0.046
Linear	2	0.9269	0.4634	1.76	0.241
NaOH (X_1)	1	0.0006	0.0006	0	0.963*
EFI (X_2)	1	0.9263	0.9263	3.51	0.103*
Square	2	4.3874	2.1937	8.32	0.014
NaOH*NaOH (X_1*X_1)	1	1.1238	1.1238	4.26	0.078*
EFI*EFI (X_2*X_2)	1	1.6040	1.6040	6.09	0.043
2-Way Interaction	1	0.1254	0.1251	0.47	0.513
NaOH*EFI (X_1*X_2)	1	0.1251	0.1251	0.47	0.513*
Error	7	1.8450	0.2636		
Lack-of-Fit	3	1.8450	0.6150		
Pure Error	4	0	0		
Total	12	7.2844			

*Not-significant, P-Value > 0.05

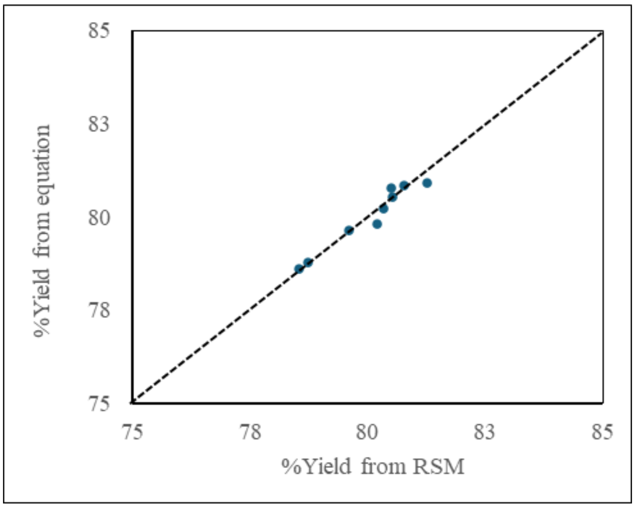

Fig. 3. Experiment and calculation percentage yield from iron electrodes.

Figure 7 displays the percentage yield of biodiesel from both experimental results and values predicted by Equation (4), shown as scattered points. The solid line represents the best-fit curve. The close alignment of most data points with the line suggests that the model accurately represents the experimental outcomes.

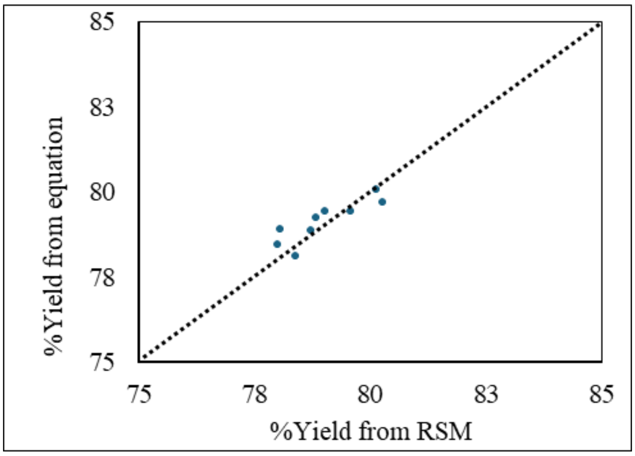

Fig. 4. Experiment and calculation percentage yield from aluminum electrodes.

3.4 *Surface Plots*

From Figure 5, it was found that when using iron electrodes, the highest biodiesel yield was 81.12%, which occurred with a catalyst concentration of 0.05% and an electric field intensity (EFI) of 125V. The lowest yield, 78.53%, was obtained with a catalyst concentration of 0.7% and an EFI of 80V.

As shown in Figure 6, the highest biodiesel yield using iron electrodes was 80.12%, achieved with a catalyst concentration of 0.6% and an electric field intensity (EFI) of 138V. In contrast, the lowest yield, 78.11%, occurred at a catalyst concentration of 0.7% and an EFI of 240V.

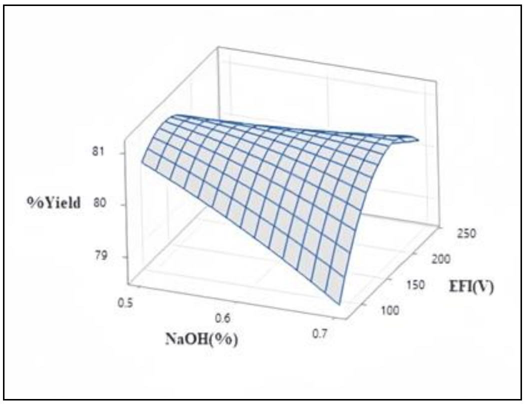

Fig. 5. Response surface plot of iron electrodes.

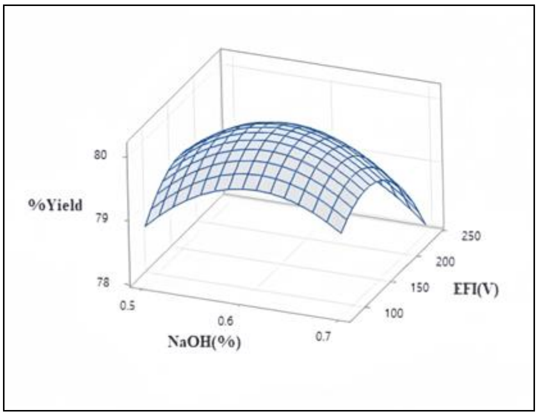

Fig. 6. Response surface plot of aluminum electrodes.

3.5 *Comparison of Iron and Aluminum Electrodes*

Table 5 shows that the highest biodiesel yield (%Yield) using iron electrodes, as determined from the analysis, was 81.12%, achieved with 0.5% of NaOH as the catalyst and an electric field intensity of 125V. For aluminum electrodes, the maximum yield was 80.12%, obtained with 0.6% sodium hydroxide (NaOH) and an electric field intensity of 138V.

Table 5. Optimum condition from RSM.

Electrodes	NaOH (%)	EFI (V)	%Yield
Irom	0.5	125	81.12
Al	0.6	138	80.12

Applying an electric field during transesterification has been shown to enhance the reaction kinetics between the oil and alcohol reactants. As elucidated by Thangaraj and Solomon [13], the passage of electric current through the electrodes induces the electrolysis of the alcohol (e.g., methanol), leading to the formation of highly reactive alkoxide ions, such as methoxide (CH_3O^-). These ions are potent nucleophiles that effectively attack the carbonyl carbon of the triglyceride ester bonds, thereby facilitating the conversion into fatty acid methyl esters (biodiesel) and glycerol. Furthermore, the electric field enhances mass transfer by lowering the surface tension between the immiscible oil and alcohol phases [8], which consequently improves reaction efficiency. An additional benefit is the enhanced separation of glycerol, as the electric field promotes the coalescence and aggregation of the polar glycerol molecules.

Fig. 7. Electrodes from iron and Al after the experiments.

The choice of electrode material, however, introduces another variable that can influence the reaction system. It has been reported that aluminum is susceptible to corrosion when in contact with biodiesel, a process that can be exacerbated by elevated temperatures or agitation [15]. This electrochemical degradation can lead to the leaching of aluminum ions into the reaction medium, which may interfere with the catalytic cycle or product purity. Conversely, iron electrodes typically exhibit superior corrosion resistance compared to aluminum. Nevertheless, iron is not entirely inert and can undergo corrosion, particularly in the presence of moisture or oxygen, resulting in the release of ferric or ferrous ions into the system. The potential catalytic or inhibitory effects of these metallic ions, originating from either electrode material as depicted in Figure 7, warrant consideration as a factor influencing the overall reaction kinetics and final yield.

4. CONCLUSIONS

This study investigates the biodiesel production from used palm oil with an electric field-assisted transesterification process. The primary focus is to compare the performance of two different electrode materials: iron (Fe) and aluminum (Al). Using a point-to-point electrode configuration with a 3 cm gap, experiments were designed via Response Surface Methodology (RSM) to determine the effects of electric field intensity (EFI) and catalyst concentration. The molar ratio of oil and methanol was fixed at 5:1, and the EFI was applied for 2 minutes.

The application of an electric field with either electrode material was found to significantly accelerate the phase separation of glycerol and enhance the biodiesel yield compared to conventional methods without an electric field. For the iron electrodes, an optimal yield of 81.12% was achieved at a catalyst (NaOH) concentration of 0.5% and an EFI of 125 V. In contrast, the aluminum electrodes yielded a comparable maximum of 80.12% but required a higher catalyst concentration of 0.6% and a greater EFI of 138 V. The overall yields obtained in this study were lower than those informed in previous works [4]-[7], [11]-[12], a discrepancy attributed to the use of ambient temperature and a lower voltage range, which were chosen to investigate the fundamental electrocatalytic effect.

A key finding is that the iron electrode system demonstrated higher efficiency, achieving a similar yield with lower catalyst and energy inputs. This phenomenon is likely due to the reaction between aluminum and the NaOH catalyst, which forms sodium aluminate and hydrogen gas. This side reaction not only consumes the catalyst but also increases the electrical resistance of the system, necessitating a higher applied voltage.

While aluminum electrodes may offer a faster initial reaction rate, iron electrodes exhibit superior chemical stability and resistance to corrosion in the alkaline environment, suggesting a longer operational lifespan. Consequently, considering long-term operational cost, material stability, and system safety, iron electrodes present a more suitable option for this application. Future research should focus on optimizing the EFI range and application duration specifically for iron electrode systems, with the aim of scaling the process for continuous or large-scale industrial operation.

ACKNOWLEDGEMENTS

The authors would like to express graditude to the Department of Mechanical Engineering, Faculty of Engineering and Industrial Technology, Silpakorn University, for the financial support.

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