

Optimization of Electrocoagulation Parameters for Peat Water Using Response Surface Methodology

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Abstract. Electrocoagulation has emerged as an environmentally friendly water treatment method by generating coagulants in situ and eliminating the need for chemical additives. Despite its promise, little research has examined the operational characteristics for tropical peat water, which is marked by high acidity and a significant presence of natural organic matter. This study investigates the effects of electrode spacing (1–2 cm) and reaction time (30–90 min) on the decrease of color, total organic carbon (TOC), and turbidity in peat water from South Kalimantan, Indonesia. A Central Composite Design (CCD) was employed in Response Surface Methodology (RSM) to identify optimal conditions. The results indicate that reduced electrode spacing and prolonged reaction time significantly enhance removal efficiency. The ideal parameters were achieved with an electrode separation of 1.514 cm and a reaction time of 74.602 min, yielding 56.16% color removal, 77.02% total organic carbon reduction, and 22.02% turbidity reduction. The high coefficients of determination ($R^2 > 0.95$) confirm the models' effectiveness in predicting treatment outcomes. This study demonstrates that CCD-RSM is a reliable tool for optimizing electrocoagulation, and the findings offer practical insights for developing cost-effective systems for treating peat water in tropical regions.

Keywords: Central Composite Design, Electrocoagulation, Optimization of Water Treatment, Peat Water, Response Surface Methodology

INTRODUCTION

Peatlands are recognized as significant carbon reservoirs in the tropics, encompassing extensive areas in Indonesia, Malaysia, and Papua New Guinea, and are

essential for global carbon storage (Qadafi *et al.*, 2020). Despite their ecological importance, peatlands pose a considerable challenge to the supply of clean water. The surface and groundwater in these regions, referred to as peat water, are often unsuitable

for direct use because of their distinct physicochemical characteristics. Peat water typically exhibits an acidic pH ($\approx 3\text{--}5$), substantial concentrations of dissolved organic matter (DOM), predominantly humic and fulvic acids, a dark coloration, and elevated levels of metals such as iron and manganese leached from deteriorated peat layers (Arifianingsih *et al.*, 2020). Prolonged exposure to untreated peat water has been associated with health risks, including gastrointestinal disorders, skin irritation, and the potential formation of carcinogenic disinfection by-products during chlorination (Tsai *et al.*, 2016).

Conventional techniques for treating peat water—specifically coagulation–flocculation, adsorption, oxidation, and membrane processes—have been extensively studied. However, these methods often face significant limitations: chemical coagulation requires large amounts of coagulants and produces excessive sludge; adsorption and filtration are impeded by fouling and media saturation; and advanced membrane systems are excessively costly and energy-demanding, making them unsuitable for rural or decentralized communities (Notodarmojo *et al.*, 2017; Padmaja *et al.*, 2020; Wenten *et al.*, 2020). These inadequacies underscore the necessity to develop creative, sustainable, and economical technology for peat water treatment.

Electrocoagulation (EC) has emerged as a feasible method by generating coagulants in situ via the electrochemical dissolution of sacrificial electrodes, destabilizing colloids, and simultaneously promoting particle flotation through hydrogen bubble production. Multiple studies have demonstrated its effectiveness in improving the physicochemical quality of peat water, notably through reductions in color, turbidity,

and dissolved metals (Ramadhan *et al.*, 2021; Rusdianasari *et al.*, 2019). Moreover, EC offers advantages such as reduced chemical consumption, less sludge production, and improved operational flexibility (Tahreen *et al.*, 2020). Nonetheless, most prior research has employed one-factor-at-a-time (OFAT) techniques, which fail to consider interactions among critical operational variables and often lead to suboptimal process performance.

To alleviate these limitations, Response Surface Methodology (RSM) has gained prominence in environmental engineering applications. RSM enables a systematic evaluation of several parameters and their interrelations with a minimized number of experimental trials, while providing statistically robust models for prediction and optimization. The Central Composite Design (CCD) is widely utilized in Response Surface Methodology (RSM) for its ability to model quadratic effects and accurately predict treatment results (Kumar *et al.*, 2024; Rangseesuriyachai *et al.*, 2024a). Previous studies employing CCD–RSM for the electrocoagulation of industrial wastewater have shown considerable predictive accuracy ($R^2 > 0.9$); still, systematic applications to tropical peat water are limited (Trigueros *et al.*, 2023).

This research is groundbreaking in its utilization of CCD–RSM to enhance electrocoagulation parameters for tropical peat water, particularly highlighting electrode spacing and reaction time—two factors often overlooked in previous studies. Unlike prior research that primarily focused on turbidity or the removal of specific pollutants, this study simultaneously evaluates color, total organic carbon (TOC), and turbidity, providing a more comprehensive understanding of treatment efficacy for the

intricate organic-inorganic matrix typical of peat water.

The objective of this study is to develop and assess statistical models employing CCD–RSM to forecast and enhance the efficacy of electrocoagulation in treating tropical peat water, focusing on the elimination of color, TOC, and turbidity. The project aims to identify optimal operational parameters that balance efficiency and practicality, thereby establishing a scientific basis for the creation of economical, chemical-free, and community-scale water treatment systems in peatland regions.

MATERIALS AND METHOD

Characterization of Peat Water

Peat water samples were obtained at Pematang Panjang Street, Sungai Lakum, in the Kertak Hanyar District of Banjar Regency, South Kalimantan. Samples were gathered in specified containers and later examined for color, total organic carbon, turbidity, and pH levels. The findings facilitate the understanding of peat water characteristics to formulate an effective treatment strategy.

Experimental Setup

Ten aluminum electrodes, each sized 12.5 cm × 9 cm × 0.1 cm, were fabricated and polished using sandpaper. The electrodes were then installed in an 8 L electrocoagulation tank of 31.5 cm × 18.5 cm × 24.4 cm, filled with peat water. The distance between the electrodes was selected based on the specified variables, specifically 1 - 2 cm. The current density was established at 6 mA/cm² with a DC power source (RIDEN® RD6012W). Peat water samples were collected at reaction times of 30, 60 and 90 min to determine color, TOC, and turbidity

removal.

After the process was completed, the electrodes were re-cleaned with sandpaper, and the experiment was repeated at different inter-electrode distances while keeping the current density and sampling time intervals constant. Figure 1 illustrates the schematic representation of the electrocoagulation process.

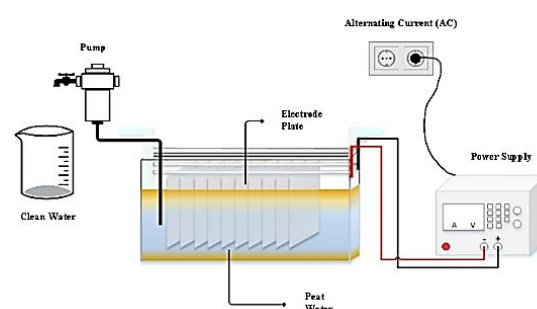


Fig. 1: Schematic representation of the electrocoagulation process

Experimental Framework

The statistical optimization experimental design was developed utilizing a CCD-type response surface methodology with Design Expert version 13 software. Design Expert Software offers an array of statistical and mathematical techniques essential for experimental design, data modeling, and identifying optimal operating conditions based on specified responses. This research uses RSM with CCD to ascertain optimal operating conditions. This study primarily examines the influence of electrode distance and contact duration on the reduction of color, TOC, and turbidity in the electrocoagulation process for peat water treatment.

The experimental design range for the CCD-type RSM was determined utilizing low, high, and alpha values, as presented in Table 1. The experimental design consists of 13 trials, including 5 runs at the center point for

replication, hence enhancing precision, as illustrated in Table 2. A lack-of-fit test was conducted to evaluate whether the developed regression model adequately represented the experimental data. The test compares the residual error of the fitted model with the pure experimental error obtained from replicated runs at the center point. A non-significant lack of fit ($p > 0.05$) indicates that the model is adequate and that no systematic variation remains unexplained within the investigated factor range.

Table 1. Experimental ranges of the independent variables used in the CCD

Variable	Unit	Low	High	- alpha	+ alpha
Electrode distance	cm	1	2	1	2
Reaction Time	min	30	90	30	90

Table 2. Experimental design matrix and response values for the electrocoagulation process

Factor		Response		
Electrode Distance (cm)	Reaction Time (min)	Color Removal (%)	TOC Removal (%)	Turbidity Removal (%)
1.5	90	59.55	79.18	23.34
1.5	60	52.85	75.61	20.84
2	90	58.07	79.84	22.84
1.5	60	52.88	71.89	19.74
1.5	60	51.99	69.86	20.19
1.5	60	54.65	72.66	21.08
1.5	30	47.70	55.10	17.84
1.5	60	53.46	74.80	21.53
2	30	41.19	51.98	16.04
1	90	61.86	82.00	25.54
1	30	51.86	65.32	19.97
1	60	57.93	78.26	23.41
2	60	48.87	74.21	19.23

To validate the optimum conditions predicted by the response surface model, an additional electrocoagulation experiment

was conducted at the predicted optimum electrode distance of 1.514 cm and electrocoagulation time of 74.602 min. The experimentally obtained removal efficiencies were subsequently compared with the predicted values generated by the regression model to evaluate the predictive capability of the model.

Analysis of Variance (ANOVA) generates interactions between process factors and response variables. ANOVA tables are frequently employed to evaluate model effectiveness. Regression analysis uses the coefficient of determination (R^2), adjusted R^2 , and predicted R^2 as metrics for performance evaluation.

The coefficient of determination (R^2) represents the proportion of variation in the response that the regression model can explain. Adjusted R^2 modifies the R^2 value by considering the number of model terms and degrees of freedom, thereby providing a more reliable measure when comparing models with different numbers of predictors. Predicted R^2 indicates the ability of the model to predict new observations that were not used in model development. A small difference between adjusted R^2 and predicted R^2 indicates that the model has good predictive ability and is not overfitted.

RESULTS AND DISCUSSION

Characterization of Peat Water

The characteristics of peat water are presented in Table 3, following standard procedures for the analysis of water and wastewater (Bridgewater *et al.*, 2012).

Table 3 shows that the peat water sample is acidic ($\text{pH} = 5$), black, and has a high concentration of organic matter ($\text{TOC} \approx 24 \text{ mg/L}$), features characteristic of tropical peatlands. These characteristics arise from

humic and fulvic acids, which not only lower pH but also augment color intensity and increase DOC levels (Ali *et al.*, 2021; Qadafi *et al.*, 2020).

Table 3. Initial characteristics of peat water used in this study

Parameter	Value
Turbidity (NTU)	29
Color (PtCo)	65.46
pH	5
Total Dissolved Solids (mg/L)	30
Total Organic Carbon (mg/L)	23.86
Organic matter (mg/L)	92.43

The peat water used in this study exhibited a color value of 65.46 PtCo and a TOC concentration of 23.86 mg/L, which were lower than the ranges of 300–1500 Pt-Co for color and 50–200 mg/L for TOC reported for highly colored tropical peat water (Qadafi *et al.*, 2023). Previous studies have shown that peat water generally has color values ranging from 300 to 1500 Pt-Co and TOC concentrations between 50 and 200 mg/L due to the abundance of humic and fulvic substances (Qadafi *et al.*, 2023). Despite the comparatively lower color and TOC concentrations, the presence of dissolved and colloidal organic matter remains relevant to electrocoagulation performance because these fractions must be destabilized and incorporated into the generated flocs. In addition, the moderate turbidity and low TDS values indicate that the contaminants are predominantly present as ultrafine colloids and organometallic complexes. Such conditions may limit turbidity removal because colloidal organic particles are more difficult to destabilize and settle than larger suspended solids. The measured turbidity and TDS values indicate the presence of ultrafine organic colloids and organometallic complexes, which are characteristic of tropical

peat water. Similar observations have been reported in previous studies, where peat water with high dissolved organic matter exhibited elevated turbidity and TDS due to humic substances and colloidal organic particles (Qadafi *et al.*, 2023; Sillanpää *et al.*, 2018).

Optimization of Peat Water Treatment Utilizing CCD

Optimal conditions were achieved using CCD. The CCD demonstrated the impact of different inter-electrode distances and reaction times on the reduction of color, TOC, and turbidity. The highest experimental removal efficiencies were observed at an inter-electrode distance of 1.0 cm and an electrocoagulation time of 90 min, resulting in color, TOC, and turbidity removals of 61.86%, 82.00%, and 25.54%, respectively. The reduced distance between electrodes and extended reaction time resulted in increased removal efficiency, highlighting the need to modify these parameters for enhanced peat water treatment. This study concentrated exclusively on two operational variables: electrode spacing and reaction time, which significantly affect coagulant production and energy efficiency in electrocoagulation. The high R^2 values (all >0.95) indicate that the chosen parameters effectively captured the system's response pattern. Thus, the limited design area can nonetheless provide reliable insights for laboratory-level process optimization.

The lack-of-fit test presented in Table 4 is crucial to the modeling process, illustrating the impact of each parameter on the reliability of the regression model (Kumar *et al.*, 2024).

In regression-based process optimization, the lack-of-fit test is a crucial diagnostic tool for evaluating the suitability of the chosen statistical model in depicting

Table 4. Results of the lack of fit test

Response	Source	Sum of squares	Df	Mean square	F value	p-value	
Color Removal Efficiency	Linear	14.10	6	2.35	2.44	0.20	Suggested
	2FI	2.28	5	0.46	0.48	0.78	
	Quadratic	2.21	3	0.74	0.77	0.57	
	Cubic	0.26	1	0.26	0.27	0.63	Aliased
	Pure Error	3.85	4	0.96			
TOC Removal Efficiency	Linear	142.19	6	23.70	4.47	0.20	Suggested
	2FI	110.91	5	22.18	4.18	0.78	
	Quadratic	5.93	3	1.98	0.37	0.57	
	Cubic	0.27	1	0.27	0.05	0.631	Aliased
	Pure Error	21.23	4	5.31			
Turbidity Removal Efficiency	Linear	1.73	6	0.29	0.56	0.75	Suggested
	2FI	1.35	5	0.27	0.53	0.75	
	Quadratic	0.42	3	0.12	0.27	0.84	
	Cubic	0.01	1	0.01	0.02	0.89	Aliased
	Pure Error	2.05	4	0.51			

the experimental data. An insignificant lack of fit ($p > 0.05$) indicates that the divergence between model predictions and experimental results is not statistically significant, suggesting that the model adequately fits the data (Kumar *et al.*, 2024). Table 4 indicates that the p-values for the color, TOC, and turbidity removal models exceed 0.05, confirming that the linear, two-factor interaction, and quadratic models do not show a significant lack of fit. This outcome validates the dependability of the regression technique and ensures precise forecasts of treatment effectiveness. Similar findings have been observed in electrocoagulation optimization studies, where RSM-based models with non-significant lack of fit displayed strong predictive accuracy for pollutant removal (Rangseesuriyachai *et al.*, 2024).

The correlation between predicted and experimental values, demonstrated by the high R^2 and adjusted R^2 in Table 5, supports the conclusion from the lack of fit test, indicating that the experimental design adequately accounted for the effects of electrode spacing and reaction time. The

alignment of model adequacy statistics (R^2 , adjusted R^2 , predicted R^2) with non-significant lack of fit is highlighted as a vital signal of reliable RSM application in water treatment optimization studies (Trigueros *et al.*, 2023).

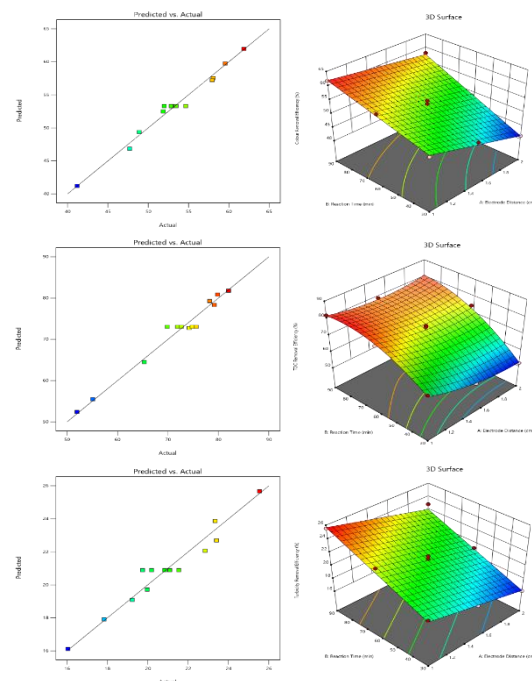


Fig. 2: Predicted versus actual values and response surface plots for the removal of (a) color, (b) TOC, and (c) turbidity.

Figure 2 illustrates the projected and actual results for the removal efficiency of color, TOC, and turbidity. The predicted values are derived using the regression model according to the equation, whereas the actual values are obtained directly from laboratory tests. The predicted values are in close agreement with the experimental values, indicating good model accuracy and reliability for color, TOC, and turbidity removal.

The comparative plots of predicted and actual values in Fig. 2 conduct a thorough assessment of the model's accuracy in reflecting the experimental outcomes for color, TOC, and turbidity reduction. The proximity of data points to the 45° line signifies that the regression models generated by RSM accurately reflected the observed responses, demonstrating minimal deviation between expected and actual values. The significant agreement confirms the strength and predictive validity of the developed models (Kumar *et al.*, 2024). The correspondence between predicted and actual responses is an established criterion for assessing model adequacy in water treatment optimization studies. Rangseesuriyachai *et al.* (2024) demonstrated a strong linear correlation between predicted and measured data, evidenced by high R^2 and adjusted R^2 values, thus confirming the reliability of CCD-RSM models in electrocoagulation processes. The consistency across the three responses-color, TOC, and turbidity-demonstrates that the experimental design adequately addressed the principal issues (electrode spacing and reaction time). Comparable outcomes have been highlighted in coagulation-flocculation research, where the alignment between predicted and actual values validated the effectiveness of natural and electrochemical

coagulants (Trigueros *et al.*, 2023).

Table 5 summarizes the statistical efficacy of the regression models using key metrics, including R^2 , adjusted R^2 , and predicted R^2 for color, total organic carbon (TOC), and turbidity removal. The consistently high R^2 values (>0.95) demonstrate that the models account for over 95% of the variability in the experimental data, signifying an exceptional correlation between observed and projected results. A high adjusted R^2 indicates that incorporating predictor variables (electrode spacing and reaction time) substantially enhances the models' explanatory power without leading to overfitting (Kumar *et al.*, 2024). The predicted R^2 values closely align with the adjusted R^2 , thus affirming the predictive reliability and external validity of the models. A significant disparity between adjusted and predicted R^2 sometimes indicates overfitting or insufficient predictive power; however, the minimal difference observed here confirms the design's robustness and the model's adequacy. Comparable findings have been recorded in investigations optimizing electrocoagulation, where high and constant R^2 values were reported as important indicators of reliable CCD-RSM models (Rangseesuriyachai *et al.*, 2024).

Table 5. Statistical parameters of the regression models

	Color Removal Efficiency	TOC Removal Efficiency	Turbidity Removal Efficiency
R^2	0.9830	0.9732	0.9506
Adjusted R^2	0.9773	0.9540	0.9407
Predicted R^2	0.9638	0.9106	0.9207

Moreover, the alignment of these statistical indicators with the non-significant lack-of-fit test (Table 4) reinforces the validity of the modeling approach. Recent studies on

the optimization of coagulation–flocculation demonstrate that high R^2 values and a strong correlation between adjusted and predicted R^2 signify the reliability of RSM models in water treatment research (Trigueros *et al.*, 2023).

The response surface plots shown in Fig. 2 indicate that decreasing the inter-electrode distance and increasing the electrocoagulation time generally improved the removal efficiencies of color, TOC, and turbidity. Based on the fitted regression model, the Design-Expert optimization module predicted an optimum condition at an electrode distance of 1.514 cm and an electrocoagulation time of 74.602 min. These values were generated by interpolation within the investigated experimental range of 1.5–2.0 cm and 30–90 min, rather than representing directly tested conditions. Under these predicted optimum conditions, the model estimated color, TOC, and turbidity removals of 56.35%, 77.11%, and 22.29%, respectively, with a desirability value of 1. The highest experimental removal efficiencies were observed at 1.0 cm and 90 min, whereas the values of 1.514 cm and 74.602 min correspond to the optimum predicted by the regression model.

Experimental validation of these optimal values resulted in color removal of 56.16%, TOC reduction of 77.02%, and turbidity removal of 22.02%. The purpose of this approach in removing color, TOC, and turbidity was to identify an effective and cost-efficient treatment strategy. By optimizing the operating conditions, the study determined the parameters that maximized the removal efficiencies of color, TOC, and turbidity during peat water treatment. The results, confirmed by experimentation, verify the reliability of the optimization strategy. The findings of this study demonstrate that improving the

electrocoagulation process using a CCD-type RSM can significantly enhance peat water treatment, resulting in improved removal of color, TOC, and turbidity. Although electrocoagulation effectively reduced color and TOC, the turbidity removal remained relatively limited. Therefore, supplementary post-treatment processes such as sedimentation, filtration, or adsorption may be necessary to further improve water clarity.

The optimum inter-electrode distance obtained in this study (1.514 cm) is consistent with the range of 1–2 cm commonly reported for electrocoagulation processes, where smaller distances improve current transfer and floc formation efficiency. Likewise, the optimum electrocoagulation time of approximately 75 min is within the 60–90 min range frequently reported in peat water and natural organic matter treatment studies. The validated TOC removal of 77.02% demonstrates substantial removal of organic matter under the predicted optimum conditions. In contrast, the lower turbidity removal observed in this study may be attributed to the presence of ultrafine colloidal particles and stable organometallic complexes that are more difficult to destabilize and settle.

CONCLUSIONS

This study established that electrocoagulation, refined using CCD-RSM, can significantly enhance the quality of tropical peat water. Electrode spacing and reaction time significantly influenced the treatment responses, with ideal settings (1.514 cm, 74.6 minutes) achieving removal efficiencies of 56.16% for color, 77.02% for TOC, and 22.02% for turbidity, corroborated by good model accuracy ($R^2 > 0.95$). These findings offer pragmatic insights for the

development of cost-efficient and environmentally friendly treatment systems, with future study suggested on pilot-scale validation, energy and cost analysis, and alternate electrode materials.

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