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Optimization of dissolved oxygen in the removal of wastewater generated in a sawmill using response surface methodology (RSM)

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Abstract: This study aims to optimize dissolved oxygen levels in treating wastewater generated during the sawmill drying process, using response surface methodology (RSM). The experimental approach, employing three independent variables centrifuge time, centrifuge RPM, and microwave power, evaluates their impact on the effectiveness of wastewater treatment based on dissolved oxygen levels. Parameter ranges are set at 5-20 minutes for centrifuge time, 15-35 for centrifuge RPM, and 100-250 Watts for microwave power. Optimization results reveal the highest dissolved oxygen value with a centrifuge time of 20.00 minutes, centrifuge RPM of 35.00, and microwave power of 100.00 Watts, yielding a maximum value of 9.85 mg/L. ANOVA analysis of the obtained data confirms the compatibility of the proposed model with experimental results ($p<0.05$), with R^2 and R^2 (adj) values calculated at 98.53% and 95.90%, respectively. These findings authenticate the reliability of the proposed model and its alignment with experimental data. In addition, the Lack of fit value obtained as a result of ANOVA analysis was found to be 0.075. Ultimately, response surface methodology (RSM) demonstrates potential contributions to optimizing dissolved oxygen in wastewater treatment experiments.
Keywords: Wastewater, Response surface methodology, Dissolved oxygen, Sawmill, Centrifuge

Kereste fabrikasında oluşan atıksuyun gideriminde çözünmüş oksijenin yanıt yüzey metodolojisi (RSM) kullanılarak optimizasyonu

Özet: Bu çalışma, kereste fabrikasındaki kurutma işlemi sırasında oluşan atık suyun arıtılmasında çözünmüş oksijenin yanıt yüzey metodolojisi (RSM) ile optimize edilmesini amaçlamaktadır. Üç bağımsız değişken olan santrifüj süresi, santrifüj RPM ve mikrodalga gücü kullanılarak yapılan deneysel yaklaşım, çözünmüş oksijen seviyelerinin atıksu arıtma etkinliği üzerindeki etkisini değerlendirmektedir. Parametre aralıkları sırasıyla santrifüj süresi 5-20 dakika, santrifüj RPM 15-35 ve mikrodalga gücü 100-250 Watt olarak belirlenmiştir. Optimizasyon sonucunda, en yüksek çözünmüş oksijen değeri santrifüj süresi 20.00 dakika, santrifüj RPM 35.00 ve mikrodalga gücü 100.00 Watt ile belirlenmiştir. Bu parametrelerle en yüksek çözünmüş oksijen değeri 9.85 mg/L bulunmuştur. Elde edilen veriler sonucunda yapılan ANOVA analizi, önerilen modelin deneysel verilerle uyumlu olduğunu ($p<0.05$) ve R^2 ile R^2 (adj) değerlerinin sırasıyla %98.53 ve %95.90 olduğunu belirtmektedir. Bu bulgular, önerilen modelin güvenilirliğini ve deneysel sonuçların modelle uyumunu doğrulamaktadır. Sonuç olarak, yanıt yüzey metodolojisi (RSM), atıksulardaki çözünmüş oksijenin optimize edilmesine yönelik yapılan deneylerde katkı sağlayabileceğini göstermektedir.
Anahtar kelimeler: Atıksu, Yanıt yüzey metodolojisi, Çözünmüş oksijen, Kereste fabrikası, Santrifüj

1. Introduction

Wood, a crucial natural asset in the forestry industry, is extensively utilized across various sectors. Through timber processing, a wide range of wood-based materials are obtained to serve industrial purposes. Activities such as harvesting, processing, drying, and cutting wood to required dimensions are typically carried out in plants involved in this process. However, these operations also lead to the generation of environmental pollutants (Adeoye et al., 2014; Li et al., 2022). Particularly in sawmills, the use of chemicals, including inorganic salts and organic compounds, poses significant pollution risks (Qiu et al., 2022). These chemicals are applied to enhance wood durability and protect against issues like blue staining, rot, and insect damage. The potential toxicity of these treatment materials to humans through inhalation, ingestion, or skin contact is a concern (ILO, 1991).

Furthermore, the environmental impact of such facilities cannot be overlooked. Wastewater produced during wood drying processes is a major concern due to its chemical and organic composition. Discharges of this wastewater have the potential to cause significant environmental damage. Moreover, the disposal of wastewater originating from industrial operations encounters obstacles in meeting rigorous environmental standards. This challenge arises from the potential adverse environmental impacts resulting from the release of untreated contaminants into the environment through wastewater, which could potentially affect human settlements (Huang and Logan, 2008; Kamali and Khodaparast, 2015; Izadi et al., 2018; Bayram et al., 2024). The environmental repercussions stemming from such

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wastewater can manifest across various aspects. Mainly, the presence of chemical compounds within the wastewater may contaminate water sources and pose a threat to aquatic ecosystems. Thus, it is need to prioritize adequate treatment of wastewater for environmental conservation. Additionally, enhancing the efficiency and efficacy of water utilization in industrial processes holds significant importance (Natarajan et al., 2018; Bayram et al., 2023).

During the evaluation of aquatic habitats, the parameter that receives consistent attention and is given top priority in each assessment is dissolved oxygen. Dissolved oxygen serves as an indicator of the ongoing biological, biochemical, and organic material load present in the aquatic ecosystem (Wetzel et al., 1979). Throughout this procedure, a range of technologies has been devised for the treatment of wastewater. Within these methodologies, the centrifugal effect and coagulation stand out as the prevailing techniques utilized for eliminating particles, reducing turbidity, and extracting natural organic substances (Chandegara and Varshney, 2014; Majekodunmi, 2015).

For optimization purposes, the response surface methodology (RSM) stands out as a frequently utilized experimental framework. Relying on experimental design principles, RSM serves as a statistical and mathematical approach aimed at optimizing the impacts of various process variables. Numerous researchers have extensively documented the capability of RSM to reduce the requisite number of experiments while acknowledging the influence of process parameters Hence, scientists widely adopt RSM to refine processes and improve equipment designs through the identification of optimal parameter configurations (Bezerra et al., 2008; Aziz et al., 2014; Yolmeh and Jafari, 2017; Ohale et. al., 2017; Behera et. al., 2018). Nevertheless, the optimization process with RSM comprises three primary stages: initially, conducting statistically designed experiments; subsequently, estimating coefficients within a mathematical model; and finally, predicting the response and evaluating the model's adequacy within the experimental context (Bezerra et al., 2008; Aziz et al., 2014; Yolmeh and Jafari, 2017; Behera et al., 2018).

The main objective of this study is to examine how the chosen experimental factors such as centrifuge duration, centrifuge revolutions per minute (RPM), and microwave power influence the dependent output parameter of dissolved oxygen levels in wastewater produced during the drying phase in sawmills.

2. Material and methods

2.1. Material

In the study, wastewater generated during the kiln drying process of red pine wood in a sawmill was utulized. As one of the pre-treatment steps, a Beko household microwave oven (with a capacity of 20 litres and dimensions of 42.5 cm wide x 26.2 cm high x 32.5 cm length) was used. The microwave oven is based on the 90-360 Watt irradiation principle. There is also a manually adjustable time. Microwave pre-treatment was carried out to break down and modify the organic matter present in the wastewater and aimed to improve its processability in the subsequent treatment stages (Ozkan et al., 2023).

Following the microwave treatment, a centrifuge instrument was used to separate the precipitate and solution. This device works on the principle of rapid rotation to separate solid and liquid components in wastewater. The centrifuge device operates between 1000-4000 RPM. It also has a manually adjustable time. After centrifugation, the sediments were separated from the solution for dissolved oxygen analysis.

The dissolved oxygen content in the solution allocated for qualitative analysis of the wastewater was determined. This serves as an indicator of the oxygen level in the wastewater and hence its quality. The measurement of dissolved oxygen using a HACH brand dissolved oxygen device (Pocket Colorimeter II) was utilized as a significant parameter to assess the environmental impacts of the wastewater and evaluate the effectiveness of treatment processes.

As the working principle of dissolved oxygen, firstly, the water sample to be measured is prepared and placed in the reservoir of the device. The device optically measures the sample in the chamber via sensors. This measurement is converted into a numerical value by an electronic circuit. The resulting numerical value is displayed on the instrument's screen or on a digital panel. This value indicates the amount of dissolved oxygen in the sample and is usually expressed in milligrams of oxygen per liter (mg/L).

2.2. Methods

The obtained wastewater was carefully measured and transferred into a 100 ml glass beaker before the start of the experiment. Subsequently, this beaker was positioned at the center of a microwave oven. The microwave oven was operated under 2.4 GHz conditions, and all samples were irradiated continuously for a period of 30 seconds to ensure homogeneous processing. Following the microwave pretreatment, a 20 ml portion of wastewater was transferred to a centrifuge tube. The centrifuge was then operated at appropriate RPM and duration to facilitate the separation of precipitates and solution (Özkan and Şahin, 2023).

In the final stage of the experiment, dissolved oxygen (DO) values were meticulously measured and recorded before each sample measurement, ensuring accurate calibration of the instrument. The samples underwent processing for varying durations ranging from 5 to 20 minutes for microwave treatment. Additionally, centrifuge rotation speeds ranged from 15 to 35 RPM, while microwave power levels were adjusted between 100 and 250 Watts.

To enable more detailed analyses and achieve efficient outcomes, the Minitab program was employed utilizing the response surface methodology (RSM). This methodology facilitated the optimization of interactions between experiments and variables, thus contributing to the effective processing of wastewater and improvement of results. The value ranges of the samples are given in Table 1.

Table 1. Ranges of variable values for experimental design

No	Name	Low	High
1	Centrifuge time (Min)	5	20
2	Centrifuge (RPM)	15	35
3	MW power (Watts)	100	250

RSM is a combination of statistical and mathematical techniques proper for modeling and analyzing situations where a response of interest is motivated by multiple factors. The goal is to maximize this response. The goal of the RSM approach is to model and optimize the output, which depends on several important aspects (Montgomery, 2017). It is a collection of mathematical and statistical attempts. Square or linear polynomial equations are used to identify the case study in order to do this. Because of this, the RSM's initial step is to identify an approximation function between the input and the output. The approximation function is the first-order model if the function establishes a linear function relationship between the input and the output (Kiran et al., 2016). Equation 1 illustrates the most basic model that may be utilized in RSM based on a first-order polynomial.

$$y=\beta_0+\sum_{i}^{k}\beta_i x_i+\varepsilon \quad (1)$$

A three-factor three level design is the most basic type of experiment design. A factor in this type of design can have one of three values: + 1, − 1, or 0, which correspond to a maximum, minimum, and the so-called center or mid-point, respectively. The following equation displays the design matrix (Box and Behnken, 1960):

$$\begin{bmatrix} \pm1 & \pm1 & 0 \\ \pm1 & 0 & \pm1 \\ 0 & \pm1 & \pm1 \\ 0 & 0 & 0 \end{bmatrix} \quad (2)$$

In a single experiment, factor values that are all at their maximum or minimum level are not suggested by Box-Behnken experimental designs. This avoids doing trials in harsh environments that can produce disappointing outcomes. According to Ferreira et al. (2007), the following equation determines the number of runs in advance:

$$N=2k(k-1)+C \quad (3)$$

Where C denotes the number of central points, and k denotes the number of components. Three layers of the three-factor A single block of 15 runs, comprising 12-factor code variations and three additional center values of the factor range, were formed using the Box–Behnken experimental design (Table 2) (Box and Behnken, 1960).

3. Result and discusion

Experimental treatment of wastewater generated during the drying process at a sawmill was conducted using three independent variables. The identification of these variables is crucial for enhancing the quality of wastewater as wastewater management poses a critical environmental concern for industrial establishments. In this context, dissolved oxygen values serve as significant indicators for evaluating wastewater treatment efficiency. Response Surface Methodology (RSM) is a statistical technique widely employed for optimizing such complex processes. The utilization of RSM provides an appropriate approach to analyze dissolved oxygen levels during wastewater treatment processes and correlate these values with specific independent variables. Equation 7 shows the dissolved oxygen values obtained from the analysis.

Dissolved Oxygen = 2.194 + 0.322 Centrifuge Time- 0.2694 Centrifuge RPM+ 0.01802 Microwave Power- 0.01000 Centrifuge Time*Centrifuge Time+ 0.00984 Centrifuge RPM*Centrifuge RPM+ 0.000103 Microwave Power*Microwave Power+ 0.01161 Centrifuge Time*Centrifuge RPM- 0.001252 Centrifuge Time*Microwave Power- 0.001673 Centrifuge RPM*Microwave Power (4)

The experimental response and the estimated values from Equation 1 are presented in Table 3. The experimental dissolved oxygen values obtained from the optimized procedure closely match the estimated values. The lowest dissolved oxygen value was achieved with a centrifuge time of 5 minutes, centrifuge RPM of 35.00, and microwave (MW) power of 175.000 Watts. Conversely, the highest dissolved oxygen value was determined with a centrifuge time of 20 minutes, centrifuge RPM of 25.00, and MW power of 100.00 Watts. It has been observed that increasing the centrifugation time significantly affects the dissolved oxygen values.

Furthermore, this study emphasizes the importance of optimization in wastewater treatment. By utilizing the identified optimal parameters, it is possible to enhance wastewater treatment efficiency and mitigate environmental impacts. Therefore, further research and development efforts in wastewater treatment can contribute to the advancement of sustainable environmental practices.

The ANOVA test applied to the experimental results is presented in Table 4 with thorough detail. The ANOVA analysis has shown that the model obtained is statistically significant ($p<0.05$), indicating compatibility between the proposed model and the experimental data. The values of R^2 and R^2 (adj) are calculated as 98.53% and 95.90% respectively, indicating a strong fit of the model to the experimental data. However, a significant nonlinearity ($p<0.05$) has been detected through the linearity test. This suggests that the model may not fully meet certain linearity assumptions. Nonetheless, the insignificance of the nonlinearity value at 0.075 ($p>0.05$) implies that the nonlinearity is not practically significant. This suggests a close correspondence between the proposed model and the experimental data.

These findings support the reliability of the proposed model and the accuracy of the experiments. However, considering the limitations identified in the linearity test, it may be worthwhile to explore conditions under which the model can be better tailored or improved. Therefore, future studies could focus on enhancing the accuracy of the model through additional analyses or exploring new methodologies for its refinement.

Table 2. Box-Behnken Experimental Design with Three Factor

Box-Behnken experimental design							
No	A	B	C	No	A	B	C
1	-1	-1	0	9	0	-1	-1
2	1	-1	0	10	0	1	-1
3	-1	1	0	11	0	-1	1
4	1	1	0	12	0	1	1
5	-1	0	-1	13	0	0	0
6	1	0	-1	14	0	0	0
7	-1	0	1	15	0	0	0
8	1	0	1				

Table 3. RSM experimental design and variable values

Standart run	Centrifuge Time (Min)	Centrifuge (RPM)	Microwave Power (Watts)	Dissolved Oxygen (Experimental)	Dissolved Oxygen (Predicted)
1	12.50	35.00	250.00	4.80	4.77
2	12.50	15.00	100.00	3.70	3.76
3	12.50	25.00	175.00	3.90	3.96
4	20.00	25.00	100.00	5.90	5.99
5	12.50	25.00	225.00	4.20	4.05
6	5.00	25.00	250.00	3.30	3.37
7	20.00	15.00	175.00	3.80	3.83
8	5.00	35.00	175.00	3.20	3.18
9	12.50	15.00	100.00	3.70	3.76
10	20.00	25.00	250.00	4.10	4.10
11	15.00	35.00	250.00	5.10	5.12
12	17.50	20.00	100.00	4.90	4.67
13	12.50	25.00	225.00	4.00	4.05
14	5.00	15.00	175.00	3.50	3.43
15	12.50	25.00	175.00	3.90	3.96

Table 4. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	7.56090	0.84010	37.36	0.000
Linear	3	5.17679	1.72560	76.74	0.000
Centrifuge Time	1	3.95274	3.95274	175.78	0.000
Centrifuge RPM	1	1.92153	1.92153	85.45	0.000
Microwave Power	1	0.18514	0.18514	8.23	0.035
Square	3	0.24906	0.08302	3.69	0.097
Centrifuge Time*Centrifuge Time	1	0.09242	0.09242	4.11	0.098
Centrifuge RPM*Centrifuge RPM	1	0.17307	0.17307	7.70	0.039
Microwave Power*Microwave Power	1	0.06743	0.06743	3.00	0.144
2-Way Interaction	3	2.15702	0.71901	31.98	0.001
Centrifuge Time*Centrifuge RPM	1	1.58241	1.58241	70.37	0.000
Centrifuge Time*Microwave Power	1	0.86751	0.86751	38.58	0.002
Centrifuge RPM*Microwave Power	1	0.09572	0.09572	4.26	0.094
Error	5	0.11243	0.02249		
Lack-of-Fit	2	0.09243	0.04622	6.93	0.075
Pure Error	3	0.02000	0.00667		
Total	14	7.67333			
Model Summary		S	R^2	R^2(adj)	
		0.15	98.53%	95.90%	

ANOVA analysis was tested at 95% confidence level and the results were found to be significant ($p<0.05$)

The normal probability plot, constructed to enhance the reliability of the study and ensure the validity of the results, demonstrates that the dissolved oxygen levels exhibit a homogeneous distribution, with minimal random variation observed during the analysis process. The normal probability plot, based on the examination of dissolved oxygen values, is presented in Figure 1. The observed straight line in the graph indicates that the residuals closely follow a normal distribution, confirming the statistically reliable measurement of dissolved oxygen levels. This reinforces the credibility of the analysis and supports the accuracy of the obtained data. Moreover, the proximity of dissolved oxygen levels to a normal distribution allows researchers to better comprehend and interpret the data.

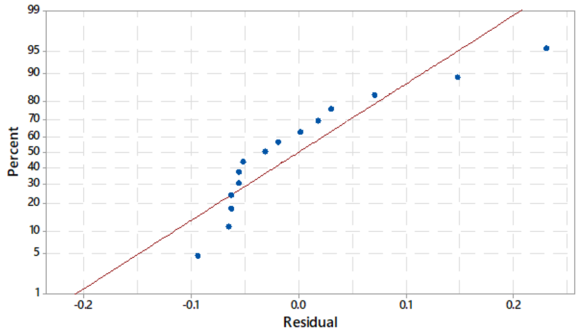

Figure 1. The normal probability plot of dissolved oxygen data

Table 5 is based on a multiple response modeling aimed at predicting dissolved oxygen levels. The experiments were conducted to investigate the effects of different centrifuge times, centrifuge RPMs, and microwave power levels on dissolved oxygen. The results indicate that under conditions of 20 minutes of centrifuge time, 35 RPM centrifuge revolutions per minute, and 100 Watt microwave power, the dissolved oxygen level was estimated to be 9.85 mg/L. This prediction was found within a 95% confidence interval of (7.08 to 12.62 mg/L), with a 95% prediction interval (95% PI) ranging from 7.06 to 12.64 mg/L. These findings demonstrate that multiple response modeling is an effective tool for understanding the impact of specific processes on dissolved oxygen levels. This data could serve as a valuable guide for optimizing water treatment processes and improving water quality.

The contour plots presented in Figure 2 illustrate the interaction between centrifuge time, centrifuge RPM, and microwave power. The curved shape of the plots suggests the significance of interaction among these factors. Upon examining the interaction between centrifuge RPM and centrifuge time, it is observed that an increase in both RPM and time leads to an increase in dissolved oxygen levels. Particularly, an increase in centrifuge time contributes to higher dissolved oxygen values, as it enhances mixing and promotes a more homogeneous distribution of dissolved oxygen in the liquid. On the other hand, in the interaction between microwave power and centrifuge time, an increase in centrifuge time is associated with higher dissolved oxygen levels. However, the increase in microwave power does not seem to significantly affect the effectiveness, indicating that higher microwave power does not substantially impact dissolved oxygen levels.

Table 5. Multiple Response Prediction

Variable	Setting
Centrifuge Time (Min)	20
Centrifuge (RPM)	35
Microwave Power (Watts)	100

Response	Fit	SE Fit	95% CI	95% PI
Dissolved Oxygen	9.85	1.08	(7.08; 12.62)	(7.06; 12.64)

Lastly, when examining the interaction between microwave power and centrifuge RPM, it is noted that the highest dissolved oxygen levels are achieved with an increase in centrifuge RPM. This suggests that higher RPM values provide better mixing, thereby encouraging a more homogeneous distribution of dissolved oxygen in the liquid.

These findings highlight the complexity of factors influencing dissolved oxygen levels and underscore the importance of considering these interactions for optimizing water treatment processes and enhancing efficiency.

When Figure 3 is examined, the Pareto chart of standardized effects demonstrates the significance of factors A (centrifuge time), B (centrifuge RPM), and C (microwave power) on the dissolved oxygen response variable. When the alpha value is set to 0.05, factors exceeding the critical threshold of standardized effects are considered statistically significant.

Upon inspection of the Pareto chart, it is evident that factor A (centrifuge time) possesses the largest standardized effect, indicating its substantial influence on dissolved oxygen levels. This suggests that variations in centrifuge time significantly impact the concentration of dissolved oxygen in the treated wastewater.

Following factor A, factor B (centrifuge RPM) also exhibits a notable standardized effect, albeit slightly smaller than factor A. This suggests that changes in centrifuge RPM also play a significant role in affecting dissolved oxygen levels, although to a slightly lesser extent than centrifuge time.

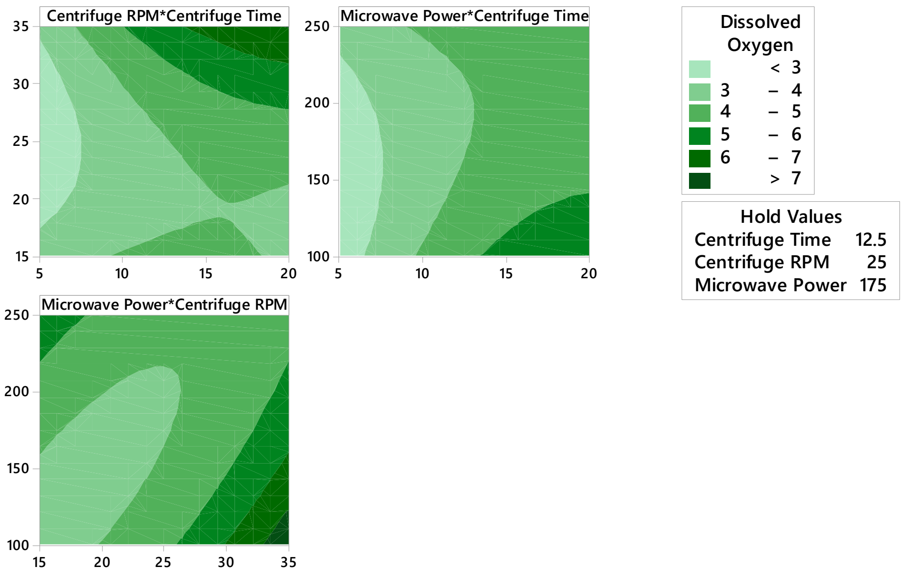

Figure 2. The contour plots of dissolved oxygen

Factor C (microwave power) demonstrates the smallest standardized effect among the three factors. While still statistically significant according to the Pareto chart, its impact may be comparatively weaker than factors A and B.

In summary, based on the Pareto chart of standardized effects, centrifuge time (factor A) emerges as the most influential factor affecting dissolved oxygen levels, followed by centrifuge RPM (factor B), with microwave power (factor C) exhibiting a smaller yet still significant effect. These findings provide valuable guidance for optimizing the process and enhancing dissolved oxygen levels in wastewater treatment.

The main effects plot in Figure 4 visually illustrates the effects of centrifuge time, centrifuge RPM, and microwave power, which are the focal parameters of the study, on dissolved oxygen levels. The graph serves as an important tool to understand the effects of each factor on dissolved oxygen levels and demonstrates how these effects vary.

Upon examining the graph, it is observed that an increase in centrifuge time leads to an increase in dissolved oxygen levels. This suggests that longer centrifuge processes contribute to a more homogeneous distribution of dissolved oxygen in the liquid, consequently resulting in higher dissolved oxygen levels.

When analyzing the effect of centrifuge RPM, it is observed that initially, an increase in RPM leads to a decrease in the average, but beyond a certain point, as RPM increases, the average also increases. In the analysis of microwave power, it is noted that an increase in microwave power leads to a decrease in the average dissolved oxygen levels. However, it is observed that after approximately 240 Watts, the average begins to rise again.

These findings emphasize the importance of considering specific parameters such as centrifuge time, centrifuge RPM, and microwave power in optimizing water treatment processes and increasing dissolved oxygen levels. Particularly, the optimization process implemented through response surface methodology, as demonstrated in various statistical analyses, can play a crucial role in improving efforts to remove pollution from wastewater.

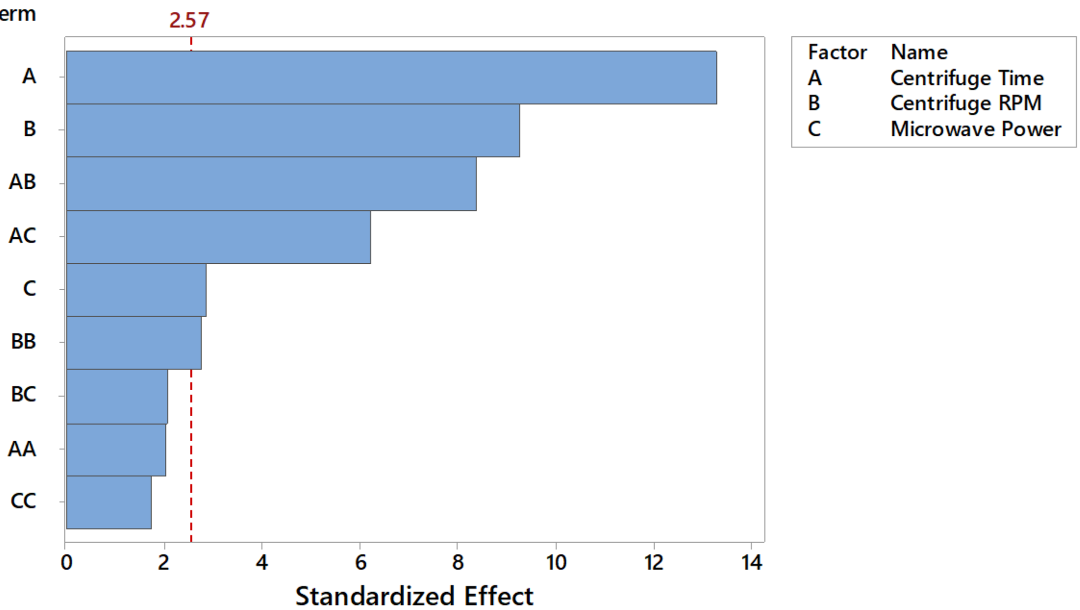

Figure 3. Pareto chart of standardized effects of factors (α=0.05)

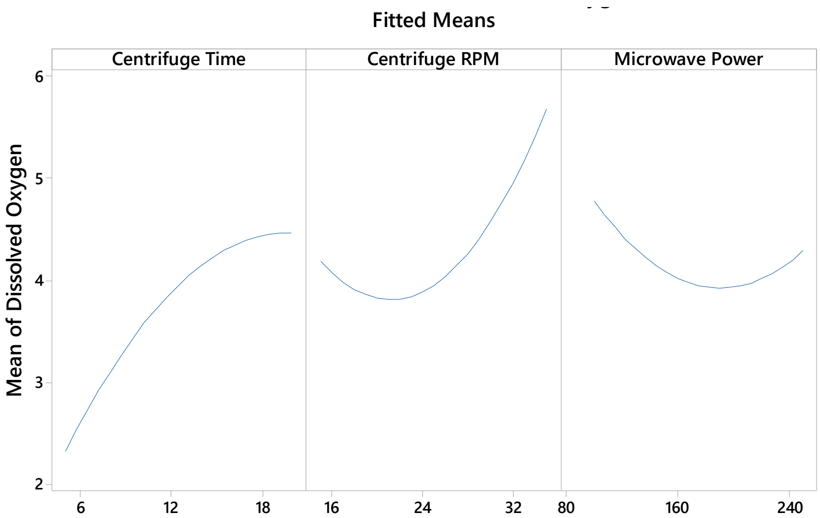

Figure 4. Main effects plot for dissolved oxygen

Conclusions

In conclusion, response surface methodology (RSM) was employed to optimize dissolved oxygen levels in the treatment of wastewater generated in a sawmill. Three main factors were examined: centrifuge time (minutes), centrifuge RPM, and microwave power (Watts). Through a series of experiments conducted using RSM, the interactions of these factors on dissolved oxygen levels were analyzed.

The obtained data indicate that centrifuge time emerges as the most influential factor affecting dissolved oxygen levels, followed by centrifuge RPM and microwave power. These findings provide a valuable roadmap for optimizing the process and may contribute to enhancing dissolved oxygen levels in wastewater treatment.

Furthermore, this study, which identified optimal conditions through the application of RSM, can lead to improving the efficiency and effectiveness of wastewater treatment processes in similar industrial environments. Future research endeavors may explore additional factors and interactions to further refine the optimization process and enhance overall wastewater treatment performance.

It is suggested that RSM could be used in future studies to determine the optimal conditions for the treatment of sawmill effluent. The finding that centrifugation time affects dissolved oxygen levels more than any other factor may identify an area of focus to improve the process. This approach could improve wastewater treatment efficiency in similar industrial settings. Furthermore, future research studies could examine additional factors and interactions to further enhance the optimization process and improve the overall wastewater treatment performance.

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