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OPTIMIZATION OF COAGULATION PROCESS PARAMETERS FOR REACTIVE RED 120 DYE USING FERRIC CHLORIDE VIA RESPONSE SURFACE METHODOLOGY

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Abstract: In this study, the removal of Reactive Red 120, a dye commonly present in textile wastewater, was investigated using Ferric Chloride ($FeCl_3$) as a coagulant. Process optimization was carried out through Response Surface Methodology based on a four-factor experimental design, considering initial pH (2–12), coagulant dose (100–500 mg/L), mixing speed (50–250 rpm), and initial dye concentration (25–250 mg/L). A second-order polynomial model was developed and evaluated by ANOVA to assess the individual and interactive effects of these parameters on color removal efficiency. The maximum removal efficiency of 96.28% was obtained at pH 3, coagulant dose 400 mg/L, mixing speed 100 rpm, and dye concentration 200 mg/L. The Response Surface Methodology model showed good agreement with the experimental data and predicted a theoretical maximum efficiency of 98.33% under optimized conditions. Overall, the results confirm that $FeCl_3$-based coagulation, when optimized by Response Surface Methodology, is a robust and scalable pretreatment option for textile wastewater, capable of achieving near-complete decolorization and providing practical operating ranges for implementation.

Keywords: Reactive red 120, Response surface methodology, Parameter optimization, Color removal, $FeCl_3$, Jar test

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1. Introduction

The textile industry is one of the largest producers of wastewater worldwide due to its high-water consumption and intensive use of chemicals. Approximately 100,000 different dyes have been identified, with an estimated annual production of about 700,000 tons. These dyes generate large volumes of wastewater not only during their application but also throughout production processes. During dyeing and finishing operations, 10–60% of dyes are discharged into water as waste, leading to an annual release of around 280,000 tons of dyes into textile effluents (Kusumlata et al., 2024). Textile wastewater represents a serious source of pollution for aquatic ecosystems due to its high color intensity, chemical oxygen demand (COD), and toxic chemical components (Yılmaz and Yılmaz, 2019). Containing both organic and inorganic pollutants, such effluents cause toxicity in aquatic organisms, disrupt the food chain through bioaccumulation, and pose carcinogenic, mutagenic, and allergenic risks to human health (Rauf and Ashraf, 2009; Holkar et al., 2016; Argun, 2025). The direct discharge of untreated effluents into receiving environments leads to contamination of drinking water resources, inhibition of photosynthetic activity due to reduced light penetration, and deterioration of ecosystem balance (Verma et al., 2012). Moreover, the recalcitrant nature of dyes limits the effectiveness of conventional biological treatment methods (Robinson et al., 2001).

Although physical, chemical, and biological methods are used for wastewater treatment, chemical coagulation–flocculation is widely preferred because of its rapid applicability, high removal efficiency, and relatively low operating cost (Yılmaz and Yılmaz, 2019; Ramadan, 2023; Kopan, 2023). Coagulation destabilizes colloidal particles and dissolved pollutants, facilitating the formation and subsequent settling of larger flocs. Commonly used coagulants include metal salts such as aluminum sulfate and ferric chloride (Bratby, 2016). Several recent studies have explored alternative adsorbents for dye removal from wastewater (Sözüdoğru et al., 2015; İrdemez et al., 2022; Tırınk and Kulakcı, 2025). Beyond textile dye effluents, the effectiveness of metal-salt coagulants has also been demonstrated in other high-strength industrial wastewaters; for instance, chemical pretreatment of pistachio-processing effluents identified suitable coagulant choices under optimized pH conditions (Tırınk et al., 2020). Ferric chloride ($FeCl_3$) stands out as an effective coagulant for the removal of color, turbidity, and organic matter due to the high charge density of Fe^{3+} ions, which rapidly destabilize colloidal particles. In particular, its strong hydrolysis products and high performance over a wide pH range make $FeCl_3$ advantageous compared to aluminum-based coagulants for the treatment of reactive dyes (Papić et al., 2000). Literature reports indicate that $FeCl_3$ can achieve color removal efficiencies exceeding 90% under optimal conditions, along with significant reductions in COD and suspended solids (Islam and Mostafa, 2018). However, process performance is highly dependent on operational parameters such as pH, coagulant dose, mixing speed, and initial pollutant concentration.

Therefore, statistical optimization of these parameters is critical for achieving high removal efficiencies while minimizing chemical consumption and operating costs (Koç and Kaymak-Ertekin, 2009). Response Surface Methodology (RSM), as a multivariate experimental design approach, provides a powerful tool to analyze parameter interactions and identify optimal conditions (Myers et al., 2016). However, studies optimizing the coagulation of reactive dyes with $FeCl_3$ using RSM remain limited in the literature. This study aims to address this gap by investigating the performance of $FeCl_3$ in the removal of RR120 dye and optimizing key process parameters—pH, coagulant dose, mixing speed, and initial dye concentration—via RSM to determine the maximum achievable color removal efficiency.

In this study, the performance of $FeCl_3$ in the coagulation of RR120 dye was systematically investigated and optimized using Response Surface Methodology. The findings revealed that pH was the most critical factor controlling removal efficiency, with acidic conditions leading to the highest performance. Under optimized parameters, a maximum experimental color removal of 96.28% was achieved, while the RSM model predicted a theoretical maximum efficiency of 98.33%. These results confirm that $FeCl_3$ coagulation, when optimized through RSM, can provide a robust and scalable pretreatment option for textile wastewater.

2. Materials and Methods

2.1. Dye and Coagulant

In this study, the anionic dye RR120 was used as the model pollutant. The chemical structure of the dye is presented in Figure 1. The dye was obtained in analytical grade and employed in the preparation of synthetic wastewater solutions for the experiments. $FeCl_3$ was selected as the coagulant. $FeCl_3$ is a commonly used metal salt coagulant in chemical coagulation processes and is known to provide high color removal efficiency (Bratby, 2016).

For the experiments, 1 g of RR120 was dissolved in distilled water and diluted to a final volume of 1000 mL to prepare a 1000 mg/L stock solution. Working solutions of desired concentration were obtained by diluting this stock solution. Standard solutions of 0 ppm, 1 ppm, 2.5 ppm, 5 ppm, 7.5 ppm, 10 ppm, 20 ppm, 30 ppm, 40 ppm, 50 ppm, 75 ppm, and 100 ppm were also prepared from the stock solution, and their absorbance values were measured at the maximum wavelength to construct the calibration curve of RR120. The maximum wavelength (λ_{max}) for RR120 was determined as 536 nm (Figure 2), and the calibration curve is presented in Figure 3.

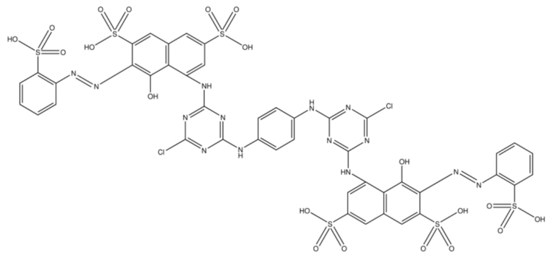


Figure 1. Chemical structure of RR120 dye.

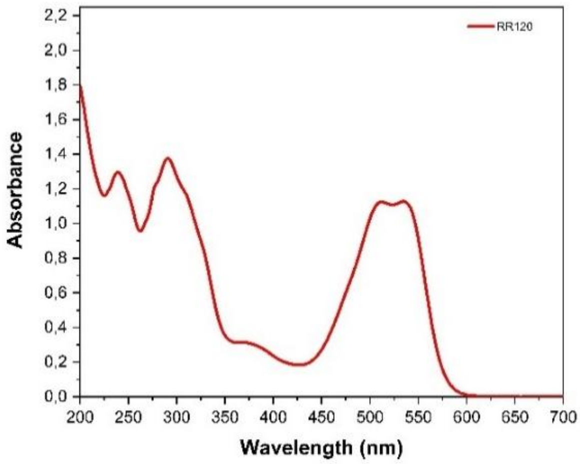


Figure 2. Determination of Wavelengths for Absorbance Measurements of RR120 Dye.

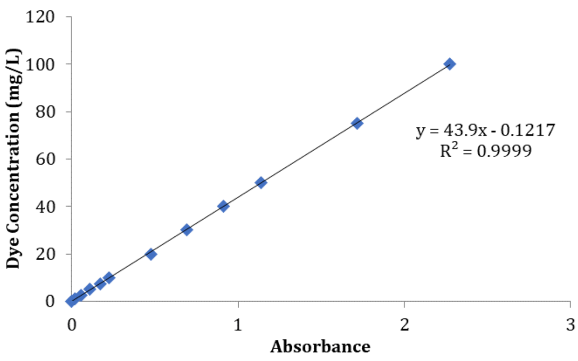


Figure 3. Calibration curve of RR120.

2.2. Experimental Setup

Coagulation/flocculation experiments were carried out using a six-paddle, variable-speed jar test apparatus (WiseStir Jar Tester JT-M6C) (Figure 4). The unit is equipped with six 1 L glass beakers, and the working sample volume was 500 mL. For pH adjustments, 0.1 N HCl and 0.1 N NaOH solutions were used.

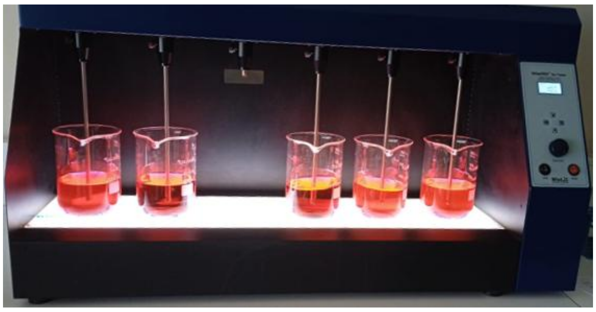


Figure 4. Jar test system.

2.3. RSM and Experimental Design

In this study, RSM and Central Composite Design (CCD) were applied to optimize process parameters for the removal of RR120 dye using $FeCl_3$ as the coagulant (Myers et al., 2016). The independent variables were defined as pH (X_1), coagulant dose (mg/L) (X_2), mixing speed (rpm) (X_3), and initial dye concentration (mg/L) (X_4). The response variable (Y) was selected as color removal efficiency (%).

The experimental design consisted of four factors, each with five levels. The factor levels were determined based on preliminary tests and optimum ranges reported in the literature. The factor levels are presented in Table 1. A total of 30 experimental runs were conducted within the design. In each experiment, rapid mixing (50–250 rpm, 5 min) followed by slow mixing (40 rpm, 20 min) was performed at the specified pH value (Verma et al., 2012). After mixing, the samples were allowed to settle for 30 minutes, and absorbance measurements of the supernatant were carried out using an OPTIZEN-POP UV-Vis spectrophotometer (λ_{max} = 536 nm).

Table 1. Factors and levels used in the experimental design for the $FeCl_3$ coagulation process

Independent Variables	Levels				
	-2	-1	0	1	2
Initial pH	2	3	7	11	12
Coagulant dosage (mg/L)	100	200	300	400	500
Stirring speed (rpm)	50	100	150	200	250
Initial dye concentration (mg/L)	25	50	100	200	250

The color removal efficiency was calculated using the experimental data according to equation 1:

$$\% \text{ Removal efficiency} = \frac{C_0 - C_t}{C_0} \times 100 \qquad (1)$$

where C_0 represents the initial dye concentration (mg/L), and C_t denotes the residual dye concentration (mg/L) measured after sedimentation.

The experimental data were modeled using a second-order polynomial model (equation 2), and the model coefficients were tested by analysis of variance (ANOVA):

$$\hat{y}_n = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

Here, Y represents the color removal efficiency; X_i and X_j are the coded independent variables; and β_0, β_i, β_{ii}, and β_{ij} represent the constant, linear, quadratic, and interaction coefficients, respectively. The validity of the model was evaluated using R^2, adjusted R^2 ($Radj^2$), and p-values (<0.05). The predictive ability of the model was confirmed through residual analysis and cross-validation.

2.4. Statistical Analysis

The experimental data were analyzed using RSM with CCD. ANOVA was employed to determine the significance of model terms, and regression coefficients (R^2 and adjusted R^2) were calculated to evaluate model adequacy. A p-value < 0.05 was considered statistically significant. All statistical analyses were performed using Minitab 16.0 software.

3. Results and Discussion

This section presents the experimental findings on the removal of RR120 dye through $FeCl_3$ coagulation, along with the modeling results obtained via RSM. Initially, the individual effects of pH, coagulant dose, mixing speed, and initial dye concentration were examined, followed by an evaluation of model adequacy, ANOVA results, and surface contour analyses.

The experimental results demonstrated that $FeCl_3$ coagulation achieved significantly higher color removal efficiencies under acidic conditions. The hydrolysis of Fe^{3+} ions at low pH leads to the formation of $Fe(OH)_3$ flocs, which are more effective in removing dye molecules from suspension (Verma et al., 2012). Similarly, Yılmaz and Yılmaz (2019) reported that optimal pH ranges are critical for achieving maximum removal in magnesium and alum coagulation processes. Increasing the coagulant dose up to 400 mg/L enhanced color removal efficiency; however, no significant improvement was observed beyond this dosage. Excessive dosing may cause restabilization of flocs and subsequently reduce removal efficiency, as also reported in the literature (Bratby, 2016). With respect to mixing speed, the optimal value was determined as 100 rpm. At lower speeds, floc formation was insufficient, while at higher speeds, the flocs tended to break apart. Furthermore, an increase in the initial dye concentration resulted in a decrease in removal efficiency. At high dye concentrations, the available Fe^{3+} ions may be insufficient to bind all dye molecules, indicating that under such conditions higher coagulant doses may be required (Robinson et al., 2001).

The statistical evaluation conducted using RSM confirmed the influence of pH, coagulant dose, mixing speed, and initial dye concentration on color removal efficiency. Based on the CCD, 30 experimental runs were carried out, yielding a maximum removal efficiency of 96.282%. The optimal conditions were determined as pH 3, coagulant dose 400 mg/L, mixing speed 100 rpm, and initial concentration 200 mg/L.

The color removal efficiency obtained from the experiments ranged between 0.04% and 96.28%. The relationship between the experimental results and model predictions is presented in Figure 5.

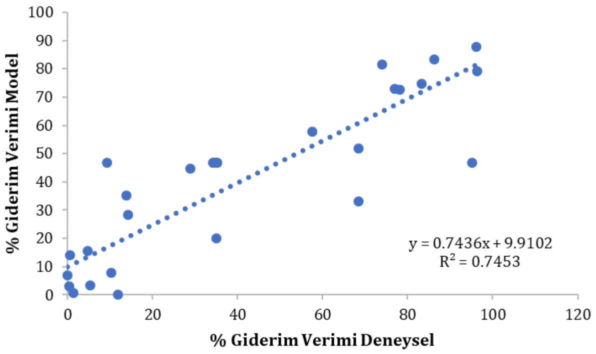


Figure 5. Correlation graph between experimental and model data.

As shown in Figure 5, a significant correlation was achieved between the experimental and model data (R^2 0.7453). This indicates that the developed model is capable of predicting color removal performance with reasonable accuracy. Under maximum removal conditions, the model yielded R^2 and adjusted R^2 (R^2adj) values of 74.53% and 50.76%, respectively.

The difference between R^2 and adjusted R^2 can be explained by the structure of the model and the number of experimental runs. The central composite design involved 30 runs, whereas the second-order model included 14 terms (four linear, four quadratic, and six interaction). In relatively small samples, the adjusted R^2 penalizes the inclusion of multiple terms more strongly, which accounts for the decrease from 0.7453 to 0.5076 (Adj. $R^2 = 1 - (1-R^2)\cdot(n-1)/(n-p-1)$, with n = 30 and p = 14). Despite this reduction, the model was statistically significant (ANOVA: F = 3.14, p = 0.018), and the lack-of-fit was not significant (p = 0.581), confirming that the model was consistent with the data. Moreover, the bounded nature of the response variable (0–100%) and the wide experimental domain (0.04–96.28%) contributed to the "moderate" overall fit. Importantly, pH was highly significant (P<0.001), and the model predictions were in close agreement with the experimental optimum (predicted 98.33% vs. observed 96.28%). These findings demonstrate that, although the overall fit is moderate, the model is sufficiently robust for optimization and for identifying the dominant factors governing the coagulation process.

By processing the experimental data into the model, an equation for calculating the percentage removal efficiency was derived, which is presented in equation 3. Using the equations obtained from the RSM, the percentage removal efficiency can be estimated without the need for additional experiments.

$$\begin{aligned}\%\,Removal\ efficiency\ &= 91 - 7.8\,X_1 + 0.058\,X_2\\ &-0.127\,X_3 + 0.264\,X_4 + 0.025\,X_1 * X_1\\ &-0.000565\,X_2 * X_2 + 0.00015\,X_3X_3\\ &-0.00117\,X_4 * X_4\ + 0.0109\,X_1 * X_2\\ &-0.0145\,X_1 * X_3 - 0.0172\,X_1 * X_4\\ &+0.00065\,X_2 * X_3 + 0.000861\,X_2 * X_4\\ &- 0.00047\,X_3 * X4\end{aligned} \quad (3)$$

To evaluate the influence of the independent variables in the experimental study, an ANOVA was conducted based on the percentage removal efficiency data. The ANOVA results for color removal efficiency are presented in Table 2. According to the analysis, the developed model was found to be statistically significant (p = 0.018). Among the factors, pH was identified as the most influential parameter on color removal efficiency (P<0.001), while the other variables individually exhibited no statistically significant effects. The quadratic terms and two-way interactions did not provide a significant contribution to the model. Furthermore, the lack-of-fit test was not significant (p = 0.581), indicating that the model was consistent with the experimental data.

According to the Pareto chart of standardized effects presented in Figure 5, only the pH factor exceeded the significance threshold (α = 0.05) and was found to have a statistically significant influence on color removal efficiency. Coagulant dose, mixing speed, initial concentration, as well as their interaction and quadratic terms, were not significant. This finding, consistent with the ANOVA results, confirms that pH is the dominant parameter governing the efficiency of the coagulation process.

The analysis of three-dimensional surface and contour plots obtained within the scope of RSM provides a more detailed illustration of the effects of process parameters on color removal efficiency (Figures 7–12).

Table 2. ANOVA analysis for percentage removal efficiency

	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Value	P-Value
	14	25157.4	1797	3.14	0.018
Linear	4	22311.7	5577.9	9.73	0
Initial pH	1	22108.6	22108.6	38.58	0
Coagulant dosage (mg/L)	1	30.3	30.3	0.05	0.821
Stirring speed (rpm)	1	159	159	0.28	0.606
Initial dye concentration (mg/L)	1	14	14	0.02	0.878
Square	4	1310.7	327.7	0.57	0.687
Initial pH * Initial pH	1	1.3	1.3	0	0.963
Coagulant dosage (mg/L)*Coagulant dosage (mg/L)	1	901.5	901.5	1.57	0.229
Stirring speed (rpm)*Stirring speed (rpm)	1	3.8	3.8	0.01	0.936
Initial dye concentration (mg/L)*Initial dye concentration (mg/L)	1	410.1	410.1	0.72	0.411
2-Way Interaction	6	1783.9	297.3	0.52	0.785
Initial pH *Coagulant dosage (mg/L)	1	305.4	305.4	0.53	0.477
Initial pH *Stirring speed (rpm)	1	135.1	135.1	0.24	0.634
Initial pH *Initial dye concentration (mg/L)	1	431.8	431.8	0.75	0.399
Coagulant dosage (mg/L)*Stirring speed (rpm)	1	168.8	168.8	0.29	0.595
Coagulant dosage (mg/L)*Initial dye concentration (mg/L)	1	691.8	691.8	1.21	0.289
Stirring speed (rpm)*Initial dye concentration (mg/L)	1	51.1	51.1	0.09	0.769
Error	15	8596.9	573.1		
Lack-of-Fit	10	5550.6	555.1	0.91	0.581
Pure Error	5	3046.3	609.3		
Total	29	33754.2			

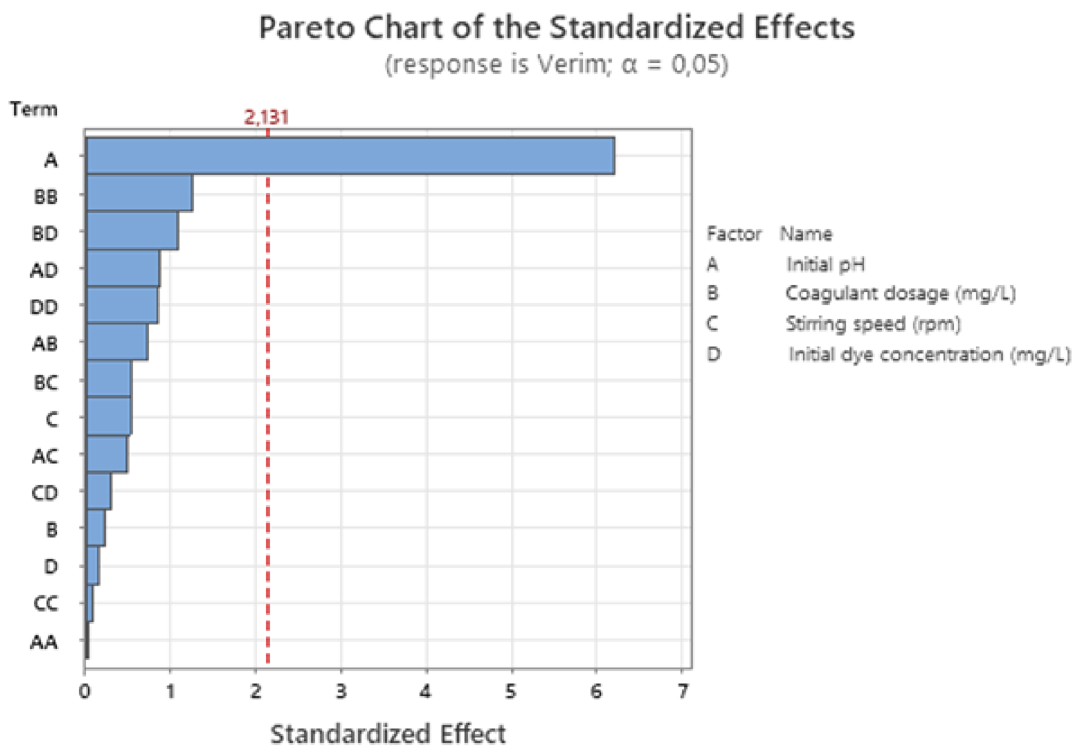


Figure 6. Pareto chart.

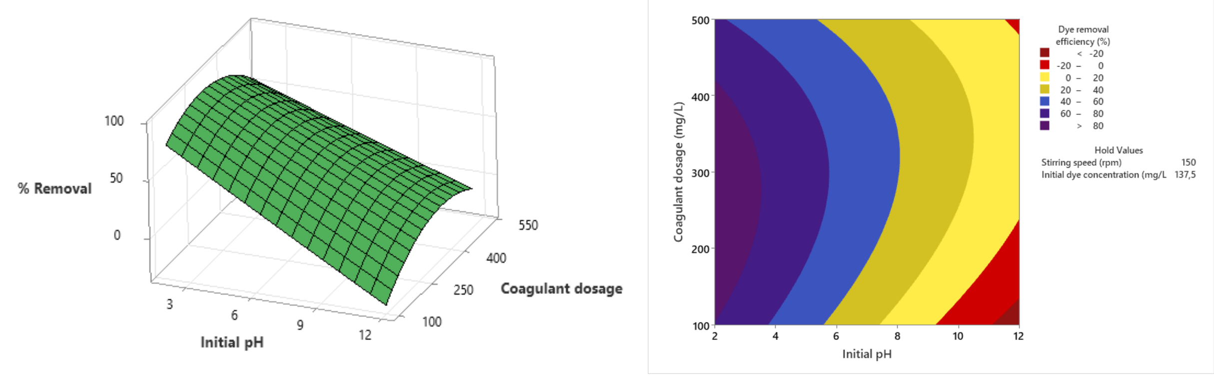


Figure 7. Surface (a) and contour (b) plots of % removal efficiency as a function of pH and coagulant dose (mg/L).

Figure 7 illustrates the interaction between pH and coagulant dose. As shown, pH is the dominant factor influencing removal efficiency. The highest efficiency was achieved under low pH conditions (pH 3–4) and at high coagulant doses. At higher pH levels, the removal efficiency decreased regardless of the coagulant dose. This behavior can be attributed to the formation of more effective hydrolysis products of $FeCl_3$ under acidic conditions. Papić et al. (2000) reported that optimal removal efficiency is achieved under low pH.

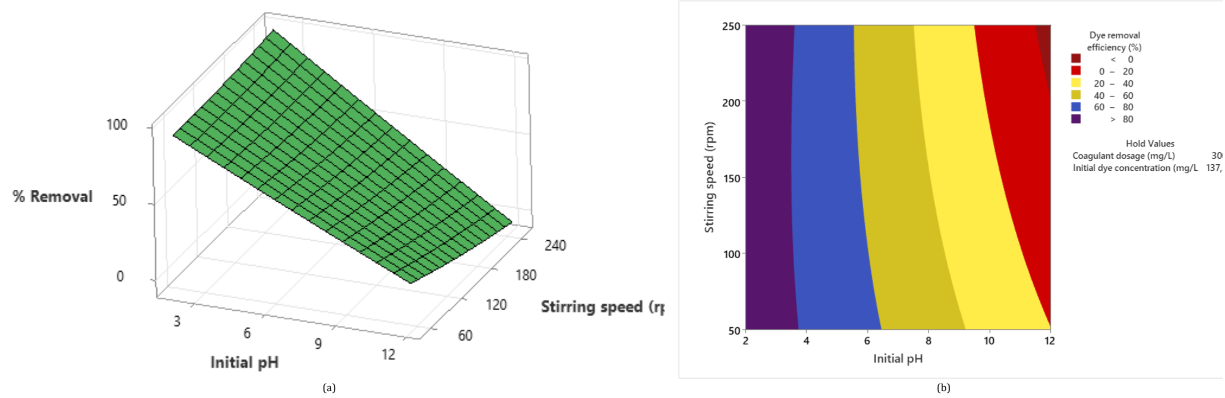
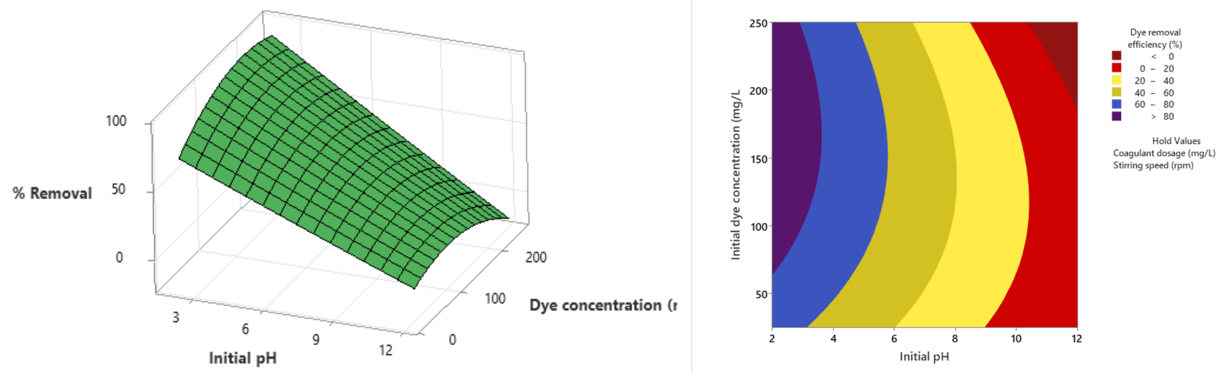


Figure 8. Surface (a) and contour (b) plots of % removal efficiency as a function of pH and mixing speed (rpm).

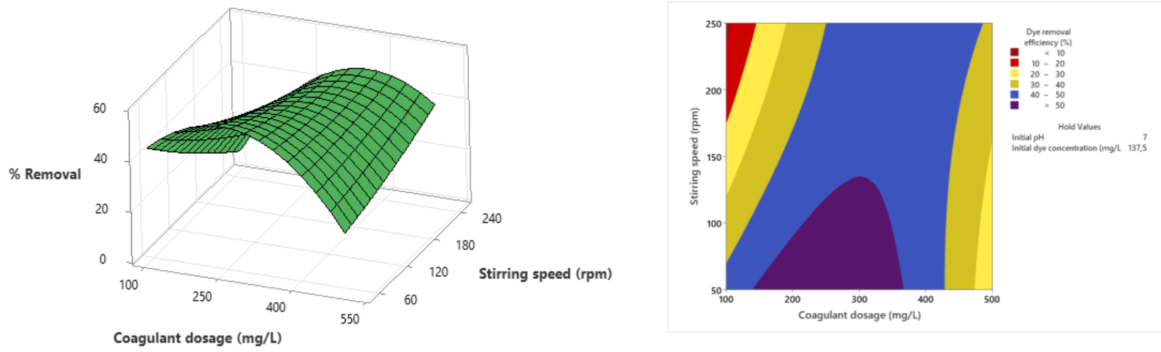
Figure 8 presents the relationship between pH and mixing speed. As observed, high removal efficiencies were obtained under acidic conditions, while variations in mixing speed had no significant effect. At higher pH levels, the efficiency remained low regardless of mixing speed. This finding indicates that pH is a more decisive factor compared to mixing speed. The literature also emphasizes that pH is among the most critical parameters in the coagulation process, whereas mixing speed plays only a secondary role, primarily influencing floc formation and stability (Bratby, 2016).



(a) (b)

Figure 9. Surface (a) and contour (b) plots of % removal efficiency as a function of pH and initial dye concentration (mg/L).

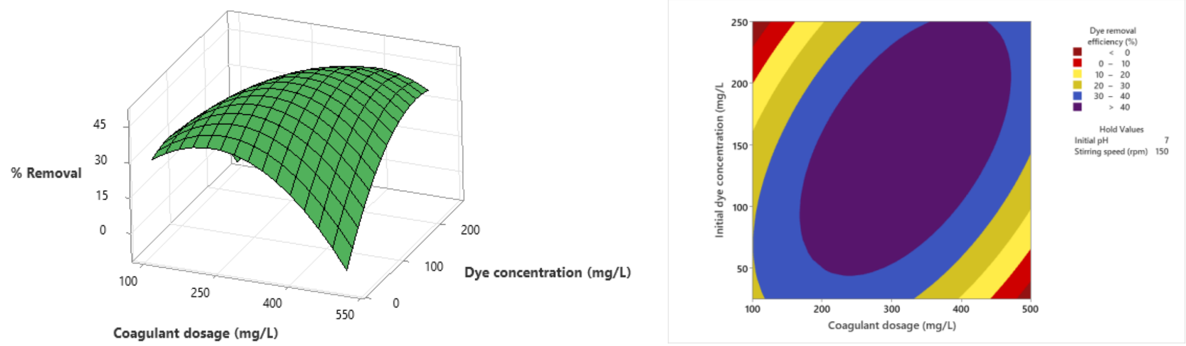
Figure 9 illustrates the interaction between pH and initial dye concentration. As shown, under low-pH conditions, removal efficiency remained relatively stable at high levels even as the initial dye concentration increased. In contrast, at higher pH values, removal efficiency was consistently low regardless of dye concentration. These results demonstrate that pH is a much more dominant parameter than initial dye concentration. Similarly, Islam and Mostafa (2018) reported that pH is a stronger determinant than concentration in the coagulation of reactive dyes with $FeCl_3$.



(a) (b)

Figure 10. Surface (a) and contour (b) plots of % removal efficiency as a function of mixing speed (rpm) and coagulant dose (mg/L).

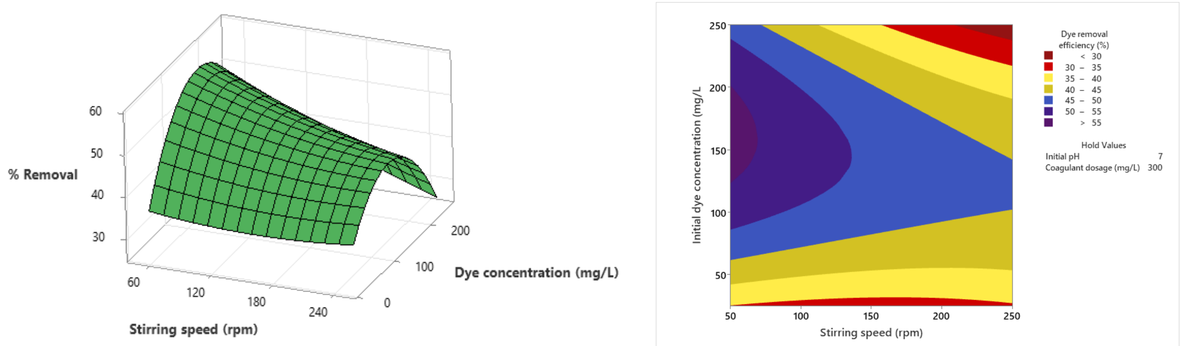
Figure 10 illustrates the interaction between mixing speed and coagulant dose. The plot shows that removal efficiency increased at low mixing speeds with high coagulant doses, but this effect was limited compared to the influence of pH. At very high mixing speeds, the efficiency decreased, likely due to the breakup of floc structures. This observation is consistent with the findings of Verma et al. (2012), who also reported that moderate mixing speeds should be preferred to achieve optimal coagulation.



(a) (b)

Figure 11. Surface (a) and contour (b) plots of % removal efficiency as a function of initial dye concentration (mg/L) and coagulant dose (mg/L).

Figure 11 depicts the relationship between initial dye concentration and coagulant dose. As observed, increasing the coagulant dose enhanced removal efficiency at lower concentrations; however, this effect became limited as dye concentration increased. This finding indicates that applying $FeCl_3$ beyond the optimum dose increases chemical consumption without providing additional benefits. Li et al. (2013) also reported that at high initial concentrations, coagulant doses above the optimum level contributed only marginally to removal efficiency.



(a) (b)

Figure 12. Surface (a) and contour (b) plots of % removal efficiency as a function of mixing speed (rpm) and initial dye concentration (mg/L).

Figure 12 examines the interaction between mixing speed and initial dye concentration. As shown, relatively higher efficiencies were obtained at low initial concentrations and moderate mixing speeds. The interaction between these two parameters was limited, and due to the dominant influence of pH, their combined effect was not decisive for overall removal efficiency.

When all the surface and contour plots presented in Figures 7–12 are evaluated, pH emerges as the most critical parameter governing color removal, while the other factors—coagulant dose, mixing speed, and initial concentration—provide only limited contributions. These findings are consistent with the results of the ANOVA analysis and the Pareto chart.

The literature also reports that while the interactions among process parameters are generally limited, defining the optimum conditions is critical for maximizing efficiency (Islam and Mostafa, 2018). Similarly, Argun et al. (2023) reported that combined treatment processes can effectively enhance the removal of azo dyes from wastewater, supporting the potential of integrated approaches for improving color removal performance. These findings highlight the dominant influence of pH but also suggest that optimizing the other factors can further enhance overall system performance. Unlike previous studies, which generally investigated $FeCl_3$ coagulation through one-factor-at-a-time experiments, the present work systematically applied RSM to model and optimize the removal of RR120 dye. This represents one of the first attempts to develop a predictive regression model for this specific dye, validated against experimental results, and highlights the dominant role of pH under varying operational conditions. Optimization is a technique aimed at identifying the most suitable levels of influential parameters to achieve the desired process outcomes. In dye removal processes, the primary goal of optimization is to define the conditions that maximize color removal efficiency (Karimifard and Moghaddam, 2018). In addition, UV/Fe^{3+} photolysis has been optimized for RR120 removal using RSM, as demonstrated by Dhruv and Abhipsa (2020), further confirming the applicability of statistical modeling in dye decolorization processes.

In this context, the optimum conditions predicted by the model, along with model estimations and validation experiments conducted under these conditions, are presented in Figure 13. As shown, the optimum color removal efficiency was calculated as 98.33%. This maximum efficiency was achieved under the following conditions: pH 2.0, coagulant dose 350.51 mg/L, mixing speed 250 rpm, and initial dye concentration 177.27 mg/L.

The enhanced efficiency at low pH can be explained by the formation of more effective hydrolysis products of $FeCl_3$ under acidic conditions, which promote rapid flocculation (Papić et al., 2000; Islam and Mostafa, 2018). The determination of an optimum coagulant dose at an intermediate level indicates that overdosing is not only economically disadvantageous but may also negatively affect floc stability (Al-Sameraiy, 2015). The relatively high optimal mixing speed reflects the need for sufficient turbulence to ensure effective mass transfer and floc growth; however, excessive turbulence may lead to floc breakage, thereby reducing efficiency (Verma et al., 2012). Finally, the optimum efficiency observed at moderate dye concentrations suggests that at high concentrations the available active sites may be insufficient, while at very low concentrations floc formation may not occur effectively.

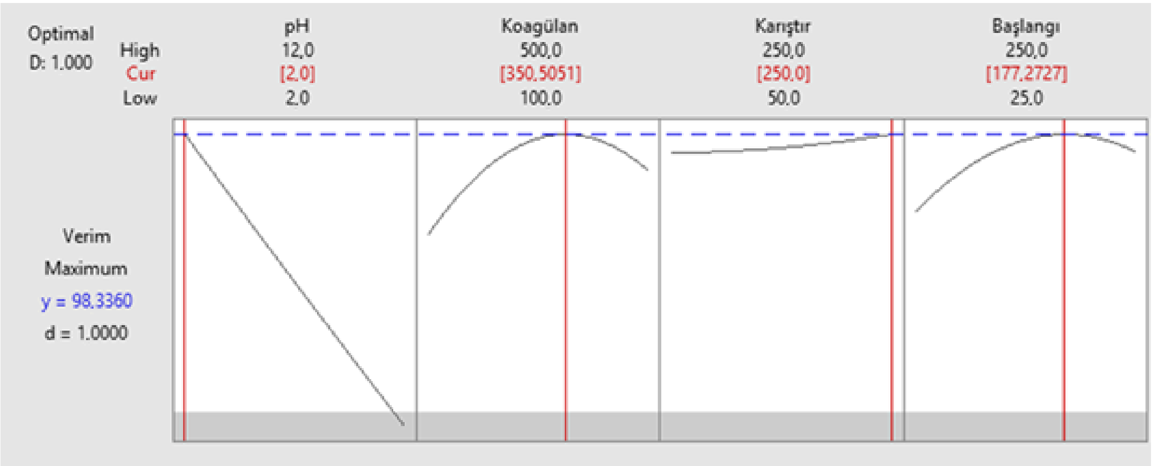


Figure 13. Optimum process parameters and maximum color removal efficiency determined by RSM.

In addition, previous optimization studies on $FeCl_3$ coagulation have also emphasized the effectiveness of RSM. For example, Kumar and Bishnoi (2017) reported color removal efficiencies as high as 99.6% in landfill leachate models, with high R^2 values confirming the reliability of the model. Sadri Moghaddam et al. (2010) likewise achieved a removal efficiency of 96.5% for the AR119 dye using an iron-based sludge known as FCS and highlighted the critical role of low pH in achieving high efficiency. These findings from the literature are consistent with the pH-driven optimum conditions and high removal efficiencies observed in the present study, further reinforcing the validity of the model and the reliability of the optimization approach. Electrocoagulation has also been applied for the removal of RR120, and Gautam et al. (2020) achieved high efficiency while optimizing process conditions through a multivariate approach, combined with an economic and sludge characterization analysis. In addition to coagulation-based studies, alternative approaches such as biosorption have also been applied for the removal of RR120. Çakmakcı (2025) reported that *Suillus collinitus* mushroom achieved an adsorption capacity of 56.82 mg/g for RR120 at pH 2, with the adsorption process best described by the Freundlich isotherm. This confirms that low pH conditions are critical not only for coagulation but also for adsorption-based processes.

4. Conclusion

In this study, the removal of RR120 dye using $FeCl_3$ as a coagulant was optimized with respect to pH, coagulant dose, mixing speed, and initial dye concentration through RSM. The experimental findings demonstrated that pH was the most influential factor affecting coagulation efficiency, whereas coagulant dose, mixing speed, and initial dye concentration had secondary effects.

The CCD experiments yielded a maximum removal efficiency of 96.28% under the conditions of pH 3, coagulant dose 400 mg/L, mixing speed 100 rpm, and initial dye concentration 200 mg/L. Furthermore, RSM optimization predicted a maximum efficiency of 98.33% at pH 2.0, coagulant dose 350.51 mg/L, mixing speed 250 rpm, and initial dye concentration 177.27 mg/L.

These results indicate that $FeCl_3$ coagulation, under suitable conditions, can achieve near-complete removal of RR120 and provides a scalable and reliable pretreatment option. The findings confirm that $FeCl_3$ is particularly effective under acidic conditions and can serve as a practical method for textile wastewater treatment. Moreover, RSM proved to be a powerful tool for parameter optimization in multivariable systems, providing results consistent with experimental validation.

Taken together, the findings revealed that pH was the most critical factor controlling removal efficiency, with acidic conditions leading to the highest performance. Under optimized parameters, a maximum experimental color removal of 96.28% was achieved, while the RSM model predicted a theoretical maximum efficiency of 98.33%. These results confirm that $FeCl_3$ coagulation, when optimized through RSM, can provide a robust and scalable pretreatment option for textile wastewater.

In conclusion, the combined use of $FeCl_3$ coagulation and RSM optimization offers both scientifically robust and industrially applicable potential for dye removal from textile wastewater.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	S.T.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

References

Al-Sameraiy M. 2015. A new approach using coagulation rate constant for evaluation of turbidity removal. Appl Water Sci, 7: 1439–1448. https://doi.org/10.1007/s13201-015-0341-8

Argun YA, Tırınk S, Çakmakcı Ö. 2023. Treatment of wastewater containing azo dyes by combined processes. Eng Sci Issues Oppor Res, 2023: 65.

Argun YA. 2025. Investigation of the adsorption of anionic and cationic dyes in the textile industry using tinder fungus (Fomes fomentarius) as a natural adsorbent. Int J Environ Res, 19(5): 1-6. https://doi.org/10.1007/s41742-025-00856-x

Bratby J. 2016. Coagulation and flocculation in water and wastewater treatment. 3rd ed. IWA Publishing, London, UK, pp: 54. https://doi.org/10.2166/9781780407500

Çakmakcı Ö. 2025. Removal kinetics, thermodynamics and adsorption mechanism of anionic and cationic textile dyes using Suillus collinitus mushroom. Chem Pap, 2025: 2-18. https://doi.org/10.1007/s11696-025-04272-5

Dhruv B, Abhipsa M. 2020. UV/Fe^{3+} photolysis process optimization using response surface methodology for decolorization of Reactive Red 120 dye simulated wastewater. In: Recent Trends in Civil Engineering: Select Proceedings of ICRTICE 2019. Singapore: Springer, Singapore, Singapore, pp: 847–865.

Gautam K, Kamsonlian S, Kumar S. 2020. Removal of Reactive Red 120 dye from wastewater using electrocoagulation: Optimization using multivariate approach, economic analysis, and sludge characterization. Sep Sci Technol, 55(18): 3412–3426. https://doi.org/10.1080/01496395.2019.1695744

Holkar CR, Jadhav AJ, Pinjari DV, Mahamuni NM, Pandit AB. 2016. A critical review on textile wastewater treatments: Possible approaches. J Environ Manage, 182: 351–366. https://doi.org/10.1016/j.jenvman.2016.07.090

İrdemez Ş, Özyay G, Ekmekyapar Torun F, Kul S, Bingül Z. 2022. Comparison of Bomaplex Blue CR-L removal by adsorption using raw and activated pumpkin seed shells. Ecol Chem Eng S, 29(2): 199–216. https://doi.org/10.2478/eces-2022-0015

Islam MR, Mostafa MG. 2018. Removal of a Reactive Dye from Synthetic Wastewater Using PAC and $FeCl_3$ Coagulants. Life Earth Sci, 13: 39–44.

Karimifard S, Moghaddam MRA. 2018. Application of response surface methodology in physicochemical removal of dyes from wastewater: A critical review. Sci Total Environ, 640–641: 772–797. https://doi.org/10.1016/j.scitotenv.2018.05.355

Koç B, Kaymak-Ertekin F. 2009. Yanıt yüzey yöntemi ve gıda işleme uygulamaları. Gida, 34(3): 185–192.

Kopan M. 2023. Endüstriyel atıksu arıtımında zeytin çekirdeği tozunun doğal pıhtılaştırıcı olarak kullanılabilirliğinin belirlenmesi. Yüksek Lisans Tezi. Karabük Üniversitesi, Lisansüstü Eğitim Enstitüsü, Karabük, Türkiye, ss: 63.

Kumar A, Bishnoi NR. 2017. Coagulation of landfill leachate by $FeCl_3$: Process optimization using Box–Behnken design (RSM). Appl Water Sci, 7(4): 1943–1953. https://doi.org/10.1007/s13201-015-0372-1

Kusumlata ., Gautam S, Kumar A, & Ambade B. 2024. Sustainable Solutions: Reviewing the Future of Textile Dye Contaminant Removal with Emerging Biological Treatments. Limnol. Rev, 24(2), 126–149. https://doi.org/10.3390/limnolrev24020007

Li JZ, Xuyin Y, Ming T, Hao J, Jiang W. 2013. Decolorization of reactive brilliant red x-3b simulated dye water by novel coagulants. Mater Sci Forum, 743–744: 665–668. https://doi.org/10.4028/www.scientific.net/MSF.743-744.665

Myers RH, Montgomery DC, Anderson-Cook CM. 2016. Response surface methodology: Process and product optimization using designed experiments. 4th ed. Wiley, London, UK, pp: 63.

Papić S, Koprivanac N, Božić AL, Meteš A. 2000. Removal of reactive dyes from wastewater using Fe(III) coagulant. Color Technol, 116(11): 352–358. https://doi.org/10.1111/j.1478-4408.2000.tb00013.x

Ramadan HAA. 2023. Çam kozalığından elde edilen doğal koagülant kullanılarak endüstriyel atıksuların arıtılması. Yüksek Lisans Tezi, Karabük Üniversitesi, Lisansüstü Eğitim Enstitüsü, Karabük, Türkiye, ss: 63.

Rauf MA, Ashraf SS. 2009. Fundamental principles and application of heterogeneous photocatalytic degradation of dyes in solution. Chem Eng J, 151(1–3): 10–18. https://doi.org/10.1016/j.cej.2009.02.026

Robinson T, McMullan G, Marchant R, Nigam P. 2001. Remediation of dyes in textile effluent: A critical review on current treatment technologies with a proposed alternative. Bioresour Technol, 77(3): 247–255. https://doi.org/10.1016/S0960-8524(00)00080-8

Sadri Moghaddam M, Moghaddam MRA, Arami M. 2010. Coagulation/flocculation process for dye removal using sludge from water treatment plant: Optimization through response surface methodology. J Hazard Mater, 175(1–3): 651–657. https://doi.org/10.1016/j.jhazmat.2009.10.058

Sözüdoğru O, Fil BA, Boncukcuoğlu R, Aladağ E, Kul S. 2015. Adsorptive removal of cationic (BY2) dye from aqueous solutions onto Turkish clay: Isotherm, kinetic, and thermodynamic analysis. Part Sci Technol, 34(1): 103–111. https://doi.org/10.1080/02726351.2015.1052121

Tırınk S, Kulakcı A S. 2025. Natural and biosorbent adsorbents for decolorization of azo dyes: a bibliometric analysis of global research trends. Mühendislik Alanında Multidisipliner Araştırma ve Değerlendirmeler, Özgür Yayınları, Harran, Türkiye, pp: 87-112. https://doi.org/10.58830/ozgur.pub776.c3232

Tırınk S, Nuhoğlu A, Kul S. 2020. Characterization of pistachio processing industry wastewater and investigation of chemical pretreatment. Environ Res Technol, 3(4): 209–216. https://doi.org/10.35208/ert.800721

Verma AK, Dash RR, Bhunia P. 2012. A review on chemical coagulation/flocculation technologies for removal of colour from textile wastewaters. J Environ Manage, 93(1): 154–168. https://doi.org/10.1016/j.jenvman.2011.09.012

Yılmaz K, Yılmaz T. 2019. Tekstil atıksuyu ve sentetik boyarmadde çözeltilerinden renk ve KOİ gideriminde alüm ve magnezyum klorürün karşılaştırılması. KSÜ J Eng Sci, 22(4): 270–280.