Desalination and Water Treatment
www.deswater.com

49 (2012) 263–271
November

1944-3994/1944-3986 © 2012 Desalination Publications. All rights reserved
doi: 10.1080/19443994.2012.719334

Optimization of chemical coagulation of real textile wastewater using Taguchi experimental design method

Ömür Gökkuş*, Yalçın Şevki Yıldız, Burhanettin Yavuz

Department of Environmental Engineering, Erciyes University, 38039 Kayseri, Turkey
Tel. +90 (352) 4374901/32802; Fax: +90 (352) 4375784; email: omurgokkus@erciyes.edu.tr

Received 24 February 2012; Accepted 1 July 2012

ABSTRACT

In the present study, optimal coagulation conditions, such as pH, coagulant dosage, slow mixing rate, rapid mixing rate, and initial concentration, were determined using the Taguchi experimental design method. Color and turbidity were considered as performance statistics. An L_{25} (5^5) orthogonal array was selected as the experimental plan for the five parameters mentioned above. Performance measure analysis was followed by performing a variance analysis, in order to determine the optimum levels and relative magnitude of the effect of parameters. The obtained results allowed concluding that the optimal conditions in terms of color and turbidity removals were initial pH of the wastewater of 9, coagulant dosage of 200 and 400 mg Al^{3+}/l, slow mixing rate of 15 and 30 rpm, rapid mixing rate of 150, and initial concentration of wastewater of $C_o/4$, respectively. At the end of the experimental studies, obtained color and turbidity removal results for real textile wastewater were 99.43 and 99.22%, respectively, at these optimum conditions.

Keywords: Chemical coagulation; Taguchi; Optimization; Color; Turbidity; Textile wastewater

1. Introduction

Nowadays, the treatment of colored waters from textile industries has attracted the attention of environmental scientists [1]. These types of wastewaters have a large variety of dyes and chemicals that make the environmental issue for textile industry not only as liquid waste, but also in its chemical content [2]. During new environmental concerns and regulations, demands are being placed on textile industries to reduce pollutants and reuse process water and chemicals [3]. Recently, there are many methods, such as physical, chemical, and biological treatments, have been widely used to handle the dye removal from wastewaters in order to comply with the regulations, which are becoming more stringent these days [4].

Generally, using technologies in the wastewater treatment have always been a tough problem due to high chemical oxygen demand (COD) concentration and poor biodegradability of dyeing wastewater [5]. Especially, water soluble textile dyes even at low concentrations can cause waste streams highly colored [6]. Biological treatment methods have been frequently used for removing organics and colored compounds of textile wastewater because of their cost-effectiveness, simple operation, and maintenance. But the nondegradable pollutants in textile industries cannot easily be degraded by conventional activated sludge process [7]. Nowadays, anaerobic biological treatment methods, which lead to the effective decomposition of azo-reactive dyes, are getting increasingly important because they are cost-effective and environmentally safe. Besides these advantages, it has also some advantages including

---

*Corresponding author.

the requiring long hydraulic residence times and thus, the need for reactors of a large volume due to the low growth yields of the anaerobic bacteria [8,9].

Chemical coagulation (CC) is one of the most common and practical methods for removing the colloidal forms of pollution from wastewater and for COD abatement. This consists in destabilizing colloids, aggregating and binding them together into flocculates; the resulting flocs can finally be removed either by settling or by flotation [10]. For this purpose, several chemicals have been conventionally used as coagulants in water and wastewater treatment, such as ferric chloride, ferrous sulfate, aluminum chloride, aluminum sulfate, and hydrated lime. Different coagulants affect different degrees of destabilization. The higher the valence of the counter-ion, the more is its destabilizing effect and the less is the dose needed for coagulation. Using Al^{3+}, particle destabilization is believed to be brought about by Al^{3+} polymers which are kinetic intermediates in the eventual precipitation of a metal hydroxide precipitate [11]. Destabilization involves first an increase of ionic strength which promotes double-layer compression, and/or the neutralization of the particle surface charge by adsorbing counter anions, using the addition of chemicals called coagulants and flocculants, usually combined with pH adjustment [10].

Recently, statistical experimental design techniques, such as response surface methodology and full or partial factorial, have frequently been used in various fields of science from chemistry to engineering and from microbiology to agriculture [12–15]. The Taguchi technique includes the design of an experiment process that uses orthogonal arrays (OA) that allow for the independent evaluation of factors through a small number of trials. This technique includes data transformation to a signal-to-noise (S/N) ratio, which is a measure of the variations presented [16]. Besides all other statistical experimental design methods, it is possible with Taguchi method that the parameters affecting an experiment can be investigated as controlling and not controlling and that the method can be applied to an experimental design involving a large number of design factors [17].

The main objective of this research was to investigate the optimum operating conditions such as initial pH and concentration of wastewater, coagulant dosage (Al^{3+}), rapid mixing rate (RMR), and slow mixing rate (SMR) by Taguchi method.

2. Materials and methods

2.1. Wastewater characteristics

The wastewater samples were obtained from a textile mill, which has indigo dying process and produce denim fabric, located in Kayseri, Turkey. Table 1 presents the characteristics of the untreated wastewater. The sample was stored at room temperature to avoid any change in their physico-chemical characteristics before use.

2.2. Chemicals and analytical methods

The initial pH of the wastewater was adjusted to desired value using 1 N NaOH (Merck) or 1 N H_2SO_4 (Merck). The Al^{3+} stock solution used as coagulant was prepared as weakly (Carlo Erbaa). All optimization experiments (such as pH, coagulant dosage, etc.) of textile wastewater were carried out with jar test apparatus (Velp VC6S). Turbidity was measured by a turbidimeter (WTW TURB 430 IR) with a range of 0–1,000 NTU (Nefolometric turbidity unit). The wavelength at maximum absorbance of textile wastewater was determined as 600 nm by a Hach–Lange spectrophotometer (DR 2500) between 300 and 800 nm. The pH was measured with a multiparameter (Hach–Lange HQ40D). Suspended solid (SS) and COD analysis for the determination of the wastewater characteristics was carried out according to standard methods [18].

2.3. Experimental procedure

CC was investigated in the batch mode by running a series of six experiments in parallel in a multiple jar-test apparatus (i.e. a six spindle mixing device), with aluminum sulfate octodecahydrate ($Al_2(SO_4)_3$ $18H_2O$ or Al^{3+}) from Carlo Erbaa as the

Table 1
The textile wastewater characteristics

Parameters	Concentration
pH	12.53
Filtered COD (mg/L)	1,925
Nonfiltered COD (mg/L)	2,233.34
SS (mg/L)	453.33
Conductivity (ms/cm)	20.47
Turbidity (NTU)	124
λ_{max} (nm)	600

Note: SS: suspended solid and λ_{max}: wavelength at maximum absorbance.

Table 2
Operating factors and their levels

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Initial pH	4	5	6	8	9
Coagulant dosage (mg Al^{3+}/L)	0	50	100	200	400
SMR (rpm)	15	30	45	60	90
RMR (rpm)	60	90	120	150	200
Initial dye concentration	C_o	$C_o/2$	$C_o/4$	$C_o/8$	$C_o/10$

chemical coagulant. The experiments were carried out at room temperature (24 ± 2°C), using 250 mL wastewater samples, by applying six different coagulant concentrations ranging from 0 to 400 mg/L (as Al^{3+}). During the tests, coagulant was first rapidly dispersed using mechanical stirring at different rotation speeds in the range of 60–200 rpm for 2 min at all the experiments. Then, CC was studied at slower stirring speeds in the range of 15–90 for 20 min. At the end of the coagulation step, samples were centrifuged at 4.000 rpm for 10 min and then analyzed to determine turbidity and color values. All experiments were performed in duplicate. During all experimental studies, all investigated variables and its levels for CC are shown in Table 2.

2.4. Statistical analysis

The variables chosen for this investigation are initial pH and concentration of wastewater, coagulant dosage (Al^{3+}), RMR, and SMR. The use of the parameter design in the Taguchi method to optimize a process with multiple performance characteristics includes the following steps:

(1) Identification of the performance characteristics and selection of the process parameters to be evaluated.
(2) Determination of the number of parameter levels for the process and possible interaction between the process parameters.
(3) Selection of the appropriate OA and assignment of process parameters to the OA.
(4) Conduction of the experiments based on the arrangement of the OA.
(5) Calculation of the performance characteristics.
(6) Analysis of the experimental results by using the performance characteristics and ANOVA.
(7) Selection of the optimal levels of process parameters.
(8) Verification of the optimal process parameters through the confirmation experiment [19,20].

The OA experimental design was chosen as the most suitable method to determine an experimental plan, L_{25} (5^5), for five parameters each with five values [20]. The experimental variables, their levels, and results of conducted experiments are given in Table 3.

In order to observe the effects of noise sources on the coagulation process, each experiment was repeated twice under the same conditions at different times. The performance characteristics were chosen as the optimization criteria. There are three categories of performance characteristics: the larger the better—this category was used to evaluate the system performance based on color and turbidity removal efficiencies—, the smaller the better, and the nominal the better. The two performance characteristics were evaluated by using Eqs. (1) and (2) [20].

Larger is better

$$\mathrm{SNL} = -10\mathrm{Log}_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \tag{1}$$

Smaller is better

$$\mathrm{SNS} = -10\mathrm{Log}_{10}\left(\frac{1}{n}\sum_{i=1}^{n}Y_i^2\right) \tag{2}$$

where SNL and SNS are performance characteristics, n is the number of repetitions done for an experimental combination, and Y_i is the performance value of the ith experiment. In the Taguchi method, the experiment corresponding to optimum working conditions might not have been done during the whole period of the experimental stage. In such cases, the performance value corresponding to the optimum working conditions can be predicted by utilizing the balanced characteristic of OA. For this, the following additive model may be used:

Table 3
Experimental variables, their levels, and results of conducted experiments corresponding to L_{25} experimental plan

Experiment No.	Variables and their levels					Dye removal efficiency (%)			Turbidity removal efficiency (%)		
	pHi	Dosage	SMR	RMR	Co	First series	Second series	Average	First series	Second series	Average
1	1	1	1	1	1	25.46	20.16	22.81	5.63	4.72	5.18
2	1	2	2	2	2	80.92	82.18	81.55	88.70	86.65	87.68
3	1	3	3	3	3	84.52	87.70	86.11	87.02	90.54	88.78
4	1	4	4	4	4	96.95	96.09	96.52	97.55	95.60	96.58
5	1	5	5	5	5	97.28	92.79	95.04	98.08	94.38	96.23
6	2	1	2	3	4	20.83	24.19	22.51	30.45	31.94	31.20
7	2	2	3	4	5	95.60	91.32	93.46	95.84	90.83	93.34
8	2	3	4	5	1	89.51	87.06	88.29	86.59	84.98	85.79
9	2	4	5	1	2	95.88	92.49	94.19	95.23	91.67	93.45
10	2	5	1	2	3	97.90	98.19	98.05	97.39	96.38	96.89
11	3	1	3	5	2	20.51	24.66	22.59	30.92	30.19	30.56
12	3	2	4	1	3	91.18	91.87	91.53	90.59	92.44	91.52
13	3	3	5	2	4	97.34	96.00	96.67	96.05	96.58	96.32
14	3	4	1	3	5	97.32	95.36	96.34	95.82	96.93	96.38
15	3	5	2	4	1	97.56	96.44	97.00	96.15	90.14	93.15
16	4	1	4	2	5	22.66	24.18	23.42	33.33	28.66	31.00
17	4	2	5	3	1	30.69	32.56	31.63	8.74	15.18	11.96
18	4	3	1	4	2	98.86	96.93	97.90	98.57	94.51	96.54
19	4	4	2	5	3	97.88	98.09	97.99	96.40	97.34	96.87
20	4	5	3	1	4	97.28	98.69	97.98	95.84	97.94	96.89
21	5	1	5	4	3	27.78	29.49	28.64	37.11	41.77	39.44
22	5	2	1	5	4	97.06	95.72	96.39	96.12	94.34	95.23
23	5	3	2	1	5	97.73	97.14	97.44	96.82	96.49	96.66
24	5	4	3	2	1	96.26	97.16	96.71	85.08	90.50	87.79
25	5	5	4	3	2	98.57	98.60	98.59	95.80	96.37	96.09

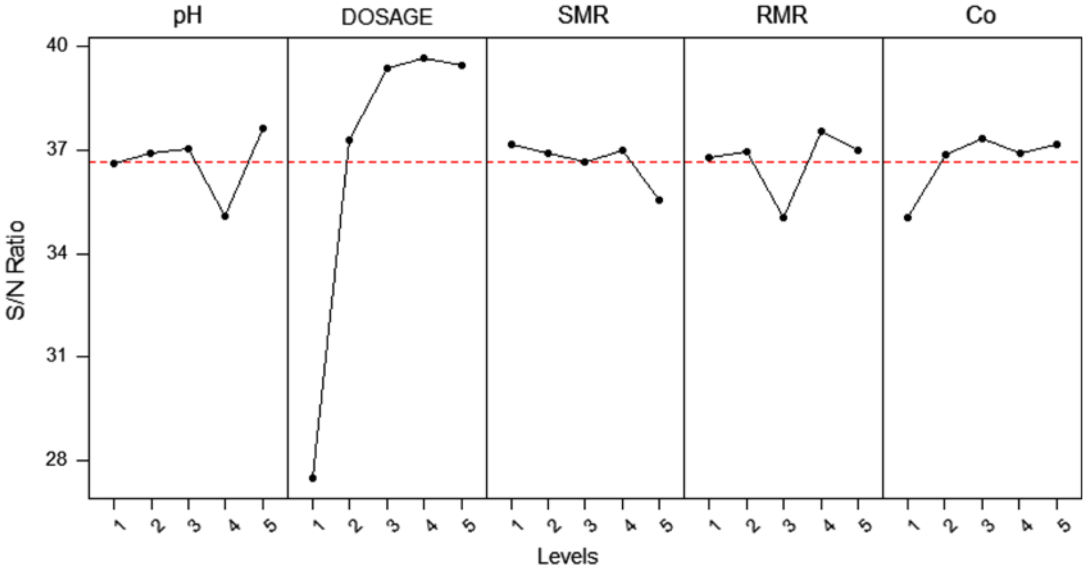

Fig. 1. The effect of each parameter on color removal.

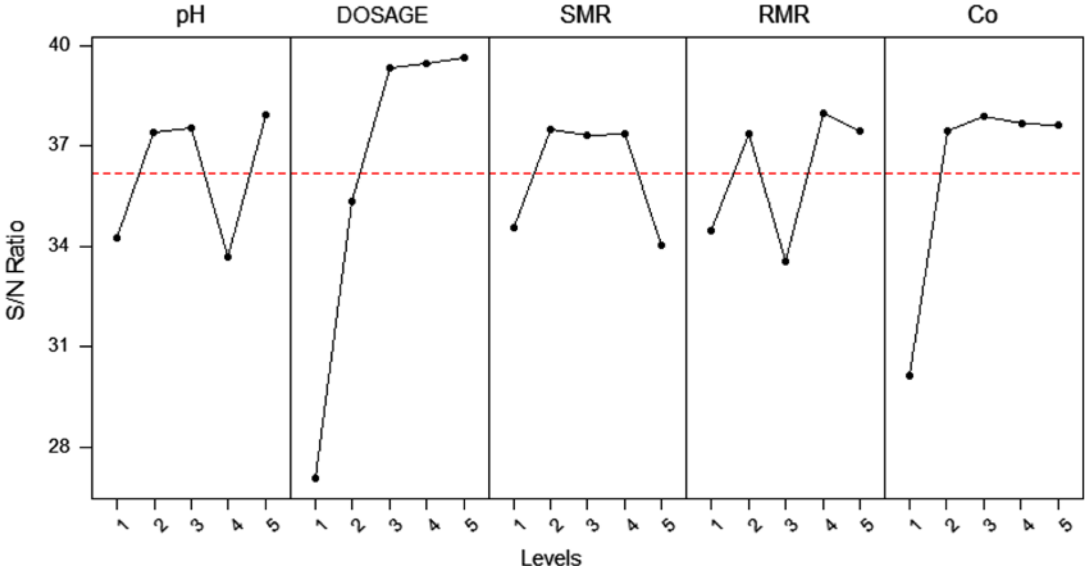

Fig. 2. The effect of each parameter on the turbidity removal.

$$Y_i = m + X_i + e_i \tag{3}$$

where m is the overall mean of performance value, X_i is the fixed effect of the parameter level combination used in the ith experiment, and e_i is the random error in the ith experiment.

If experimental results are stated in a percentage (%), before evaluating Eq. (3), the Ω transformation of percentage values should be applied first using Eq. (4) by which values of interest are also determined later by carrying out a reverse transformation by using the same equation [21]:

$$\Omega\ (\mathrm{db}) = -10\mathrm{Log}\left(\frac{1}{P} - 1\right) \tag{4}$$

where Ω (db) is the decibel value of percentage value subject to omega transformation and P is the percentage of the product obtained experimentally. Since Eq. (3) is a point estimation which is calculated by using experimental data in order to determine whether the additive model is adequate or not, the confidence limits for the prediction error must be evaluated [20]. The prediction error is the difference between the observed Y_i and the predicted Y_i. The confidence limits for the prediction error are as follows:

$$\mathrm{Se} = \pm 2\sqrt{\left[\frac{1}{n_0}\right]\sigma_e^2 + \left[\frac{1}{n_r}\right]\sigma_e^2} \tag{5}$$

$$\sigma_e^2 = \frac{\text{sum of squares due to error}}{\text{degrees of freedom for error}} \tag{6}$$

$$\frac{1}{n_0} = \frac{1}{n} + \left[\frac{1}{n_{A_i}} - \frac{1}{n}\right] + \left[\frac{1}{n_{B_i}} - \frac{1}{n}\right] + \left[\frac{1}{n_{C_i}} - \frac{1}{n}\right] + \cdots \tag{7}$$

where Se is the two standard deviation confidence limit, n is the number of rows in the matrix experiment, n_r is the number of repetitions in the confirmation experiment, and $n_{A_i}, n_{B_i}, n_{C_i}, \ldots$ are the replication numbers for the parameter levels A_i, B_i, C_i, …. If the prediction error is outside these limits, the possibility that the additive model is not adequate should be suspected. Otherwise, the additive model can be considered to be adequate.

A verification experiment is a powerful tool for detecting the presence of interactions among the control parameters. If the predicted response under the optimum conditions does not match the observed response, it implies that the interactions are important. If the predicted response matches the observed response, it then implies that the interactions are probably not important and that the additive model is a good approximation [22].

The order of the experiments was obtained by inserting parameters into the columns of OA and L_{25} (5^5) which were chosen as the experimental plan given in Table 3. The order of experiments was made random in order to avoid noise sources which had not been considered initially and which could take place during an experiment and affect results in a negative way.

3. Results and discussion

3.1. Determination of optimum parametric levels

Experimental results in respect to the model which was designed with the Taguchi method are given in Table 3 and also, all intervals of variables are stated in Table 2. During the study, all of the experimental analysis were carried out with two repetitions, and both color and turbidity results are expressed as percentage of removal (%) in terms of the following equation.

$$\%\ \text{removal} = [(\text{initial value} - \text{final value})/\text{initial value}] \times 100 \tag{8}$$

The data collected from the experiments were analyzed using the (MINITAB Release 13.20) computer software package for evaluation of the effect of each parameter on the optimization criterion. The obtained results are shown in Figs. 1 and 2.

The numerical value of the maximum point in each graph shows the best value of that particular parameter, given in Table 2 for each parameter, and they indicate the optimum conditions in the range of the experimental conditions.

3.1.1. Determination of the optimum pH value

Fig. 1 illustrates the effects of all performance criteria on color removal efficiency. As it is seen on Table 1, original pH value of the wastewater is 12.53. The pH experiments performed within the investigated range showed that optimal pH value was 9 (fifth level) for the best color removal efficiency.

As it is seen from Fig. 2, similar to color removal, the best turbidity removal was obtained at pH 9 (fifth parametric level).

3.1.2. Determination of the optimum dosage value

It is clear from Fig. 1 that increasing Al^{3+} concentrations enhanced color removal efficiency as it would be expected. For studied interval (0–400 mg Al^{3+}/l), increase in the coagulant dosage more than 200 mg Al^{3+}/l did not affect significantly color removal performance. The reason of this behavior of the system is restabilization due to excessive dosing [5].

Fig. 2 shows the effect of the applied coagulant dosage (as mg Al^{3+}/l) on the turbidity removal. The optimal level of the coagulant concentration was determined as 400 mg Al^{3+}/l. It is also shown in Fig. 2, results almost the same at fourth and fifth levels. Therefore, fourth (200 mg Al^{3+}/l) level of the coagulant concentration in terms of treatment cost may provide sufficient turbidity removal efficiency. Alum $Al_2(SO_4)_3$ reacts with hydroxides to form $Al(OH)_3$ in relatively high concentrations. The colloidal particles are entrapped either during floc formation or just after. The occurring coagulation is commonly called as sweep coagulation [23].

3.1.3. Determination of the optimum SMR and RMR values

The optimal SMR was determined as first parametric level (15 rpm) in terms of color removal. If the effect of RMR on color removal performance would be evaluated, the most color removal efficiency was obtained at fourth parametric level (150 rpm). Increasing RMR values higher than 150 rpm negatively affected color removal performance.

On the other hand, the effect of RMR on turbidity removal would be evaluated; the best removal rate was achieved at fourth parametric level (150 rpm). However, as shown in Fig. 2, turbidity removal rates are almost the same at second and fourth levels and so, 90 rpm of RMR can be said to be sufficient in terms of process economy. Likewise, SMR essays show that second and fourth levels given the best removal results. But 30 rpm of SMR (second parametric level) can be chosen as the optimum level.

3.1.4. Determination of the optimum initial dye concentration value

In the scope of the study, the last parameter investigated was initial dye concentration (C_o). The highest color removal efficiency was obtained at third parametric level ($C_o/4$) in terms of initial wastewater concentration. It is clear from Fig. 1 that high initial dye concentrations decreases color removal efficiencies. On the other hand, dilution of dye concentration more than $C_o/4$ does not affected significantly color removal performance. This is because, water-soluble structure of dye contained in the wastewater depending on the typical properties, and occurence non-removal consistent color after a certain removal rate.

As it is seen from Fig. 2, similar to color removal, the most turbidity removal depending on initial wastewater concentration was obtained at third parametric level ($C_o/4$). If it would be remembered that turbidity occurs by mainly reason of SSs which are present in wastewater, and it is also an optical property causing refraction and adsorption of light in the solution, so, it can be said that increasing initial dye concentration decreases turbidity removal efficiencies. In addition, dilution of the dye concentration more than a certain rate ($C_o/2$) does not affect significantly turbidity removal performance of the CC as such in color removal. Merzouk et al. (2011) reported that when initial dye concentration reduced, overdosing coagulant led to adverse effect on CC because of increasing colloidal stability [10].

3.2. Determination of contribution ratios and statistical analysis

In this part of the study, it was aimed to determine contribution ratios (Cr) of each factors have effected on color and turbidity removal with CC. Firstly, in order to test the predicted results, confirmation experiments were carried out once at the same working conditions. Thus, some confirmation runs also including optimum working conditions were made and presented in Table 4. By using Eq. (4), the Ω transformation was applied to the estimated results (predicted) to be able to express as a percentage of the results given in Table 4.

The optimal levels of these factors are the levels with the maximum performance measures that is with minimum variability. It is clear from performance measures and ANOVA that factor coagulant concentration significantly affect the variation in the response. The other effective factors can be ordered as pH, RMR Co, and SMR in terms of high Cr values, respectively. The Cr of each factor to the color and turbidity are presented in Tables 5 and 6, respectively.

According to Taguchi, the use of the *F* ratios in an ANOVA analysis is only helpful for the qualitative evaluation of whether factorial effects exist. For quantitative evaluation, this is something that can be achieved through the use of a Cr. The Cr of a main factor effect is its contribution (in percentage terms) to

Table 4
Optimum experimental conditions predicted and observed removal efficiency values

Perform. criteria	pHi		Dosage (mg Al^{3+}/L)		SMR (rpm)		RMR (rpm)		C_o (mg/L)		Observed (%)	Predicted (%)	Confidence limit (%)
	Level	Value	Level	Value	Level	Value	Level	Value	Level	Value			
Color Removal	5	9	4	200	1	15	4	150	3	$C_o/4$	98.63	99.26	80.98–100
Turbidity Removal	5	9	5	400	2	30	4	150	3	$C_o/4$	100	99.03	78.28–100

Table 5
Results of the ANOVA and Cr values on color removal performance with CC

Source	DF	Seq SS	Adj MS	F	Cr
pH	4	1546.5	386.6	8.2	3.06
Dosage	4	37727.6	9431.9	200.13	**84.48**
SMR	4	996.1	249	5.28	1.82
RMR	4	1470.7	367.7	7.8	2.89
C_o	4	1328.8	332.2	7.05	2.57
Error	29	1366.7	47.1		
Total	49	44436.3			

Table 6
Results of the ANOVA and Cr values on turbidity removal performance with CC

Source	DF	Seq SS	Adj MS	F	Cr
pH	4	1894	473.5	7.71	3.57
Dosage	4	33487.1	8371.8	136.33	**71.99**
SMR	4	1322	330.5	5.38	2.33
RMR	4	2253.4	563.4	9.17	4.35
C_o	4	5437.9	1359.5	22.14	11.24
Error	29	1780.9	61.4		
Total	49	46175.2			

the total variability of the experimental results [23]. The Cr can be achieved by dividing the source's net variation by SS_{total}, which is given as follows:

$$\mathrm{Cr} = \frac{\mathrm{Seq\ SS} - (\mathrm{DF} \times \mathrm{AdjMS}_{\mathrm{Error}})}{\mathrm{Seq\ SS}_{\mathrm{Total}}} \tag{9}$$

It is clearly seen from the Cr column of Tables 5 and 6 that the highest contributors to the variability of the experimental results are Al^{3+} concentration, with the Al^{3+} concentration accounting for more than 85 and 71% of total variation for color and turbidity, respectively.

From the fact that the behavior of the CC process obtained from the confirmation experiments are within the calculated confidence intervals, it can be said that experimental results are within a "5% error" (Tables 5 and 6). These results show that the interactive effects of the parameters are, indeed, negligible and also prove that the Taguchi method can be applied successfully for the determination of optimum color and turbidity removal with CC process, with only a very limited number of experiments and shorter time being needed to obtain the optimum values of the influential parameters.

4. Conclusions

In this study, it was demonstrated that the applicability of Taguchi method to CC as a statistical approach, and, at the end of the study, optimum experimental conditions were determined. Also, Cr values of each variable which have an effect on system performance were determined at these optimum conditions. It can be said that CC is an effective method for color and turbidity removal from real textile wastewater.

According to experimental results, the optimum parametric values within investigated range have been suggested for the color removal as the pH 9, 200 mg Al^{3+}/l of coagulant concentration, 15 rpm of SMR, 150 rpm of RMR, and $C_o/4$ of initial dye concentration. On the other hand, turbidity removal results indicated that optimum removal efficiencies were achieved at pH 9, 400 mg Al^{3+}/l of coagulant concentration, 30 rpm of SMR, 150 rpm of RMR, and $C_o/4$ of initial dye concentration. Under these optimum conditions, removal efficiencies for color and turbidity were 98.63 and 99.22%, respectively.

The ANOVA analyses which were carried out in the scope of the study showed that the most significant parameters for color and turbidity were coagulant concentration (as Al^{3+}). The Cr value of Al^{3+} equals to about 86 and 72%, respectively. In view of color and turbidity removal efficiencies, Cr of the coagulant concentration is the biggest one among the other Cr values, so it is the most effective parameter on process.

Acknowledgments

This research was supported by the FBA-10-2966 project of the Research Fund of Erciyes University and performed in the laboratories of the Environmental Engineering Department, Engineering Faculty, Erciyes University.

References

[1] K. Lu, X.L. Zhang, Y.L. Zhao, Z.L. Wu, Removal of color from textile dyeing wastewater by foam separation, J. Hazard. Mater. 182 (2010) 928–932.

[2] A.A. Ahmad, B.H. Hameed, Effect of preparation conditions of activated carbon from bamboo waste for real textile wastewater, J. Hazard. Mater. 173 (2010) 487–493.

[3] A.R. Tehrani-Bagha, N.M. Mahmoodi, F.M. Menger, Degradation of a persistent organic dye from colored textile wastewater by ozonation, Desalination 260 (2010) 34–38.

[4] S.M. Lam, J.C. Sin, A.Z. Abdullah, A.R. Mohamed, Degradation of wastewaters containing organic dyes photocatalysed by zinc oxide: A review, Desalin. Water Treat. 41 (2012) 131–169.

[5] S. Liu, Q. Wang, H. Ma, P. Huang, J. Li, T. Kikuchi, Effect of micro-bubbles on coagulation flotation process of dyeing wastewater, Sep. Purif. Technol. 71 (2010) 337–346.

[6] V.J. Leebana, H. Santhanam, K. Geetha, S.A. Raj, Biodegradation of direct golden yellow, a textile dye by *Pseudomonas putida*, Desalin. Water Treat. 39 (2012) 1–9.

[7] Z. Fu, Y. Zhang, X. Wang, Textiles wastewater treatment using anoxic filter bed and biological wriggle bed-ozone biological aerated filter, Bioresour. Technol. 102 (2011) 3748–3753.

[8] D. Georgiou, A. Aivasidis, Decoloration of textile wastewater by means of a fluidized-bed loop reactor and immobilized anaerobic bacteria, J. Hazard. Mater. B135 (2006) 372–377.

[9] S. Sandhya, K. Sarayu, K. Swaminathan, Determination of kinetic constants of hybrid textile wastewater treatment system, Bioresour. Technol. 99 (2008) 5793–5797.

[10] B. Merzouk, B. Gourich, K. Madani, C. Vial, A. Seki, Removal of a disperse red dye from synthetic wastewater by chemical coagulation and continuous electrocoagulation. A comparative study, Desalination 272 (2011) 246–253.

[11] M.H. Al-Malack, N.S. Abuzaid, A.H. El-Mubarak, Coagulation of polymeric wastewater discharged by a chemical factory, Water Res. 33 (1999) 521–529.

[12] N. Yusoff, M. Ramasamy, S. Yusup, Taguchi's parametric design approach for the selection of optimization variables in a refrigerated gas plant, Chem. Eng. Res. Des. 89 (2011) 665–675.

[13] J.M. Parks, On stochastic optimization: Taguchi Methods demystified; its limitations and fallacy clarified, Probab. Eng. Mech. 16 (2001) 87–101.

[14] K. Yang, E.C. Teo, F.K. Fuss, Application of Taguchi method in optimization of cervical ring cage, J. Biomech. 40 (2007) 3251–3256.

[15] I. Turkmen, R. Gul, C. Celik, A Taguchi approach for investigation of some physical properties of concrete produced from mineral admixtures, Build. Environ. 43 (2008) 1127–1137.

[16] M.P. Elizalde-Gonzalez, L.E. Garcia-Diaz, Application of a Taguchi L_{16} orthogonal array for optimizing the removal of Acid Orange 8 using carbon with a low specific surface area, Chem. Eng. J. 163 (2010) 55–61.

[17] S. Irdemez, Y.S. Yildiz, V. Tosunoglu, Optimization of phosphate removal from wastewater by electrocoagulation with aluminum plate electrodes, Sep. Purif. Technol. 52 (2006) 394–401.

[18] APHA, AWWA and EF Standard Methods for the Examination of Water and Wastewater, 20th ed., American Public Health Association, Washington, DC, 1998.

[19] O. Kucuk, M.M. Kocakerim, M. Copur, A. Yartasi, Optimization of dissolution of ulexite in $(NH_4)_2SO_4$ solutions, Can. Metall. Q. 44 (2005) 1–6.

[20] M.S. Phadke, Quality Engineering Using Robust Design, Prentice Hall, Englewood Cliffs, NJ, 1989, pp. 61–292.

[21] G. Taguchi, System of Experimental Design, Quality Resources, American Supplier Institute, Dearborn, MI, 1987, p. 108.

[22] S. Irdemez, N. Demircioğlu, Y.S. Yildiz, Z. Bingul, The effects of current density and phosphate concentration on phosphate removal from wastewater by electrocoagulation using aluminum and iron plate electrodes, Sep. Purif. Technol. 52 (2006) 218–223.

[23] S. Aber, D. Salari, M.R. Parsa, Employing the Taguchi method to obtain the optimum conditions of coagulation–flocculation process in tannery wastewater treatment, Chem. Eng. J. 162 (2010) 127–134.