Optimizing the Coagulation Dose Considering Multi Factors: A Design of Experiment Approach

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Abstract

Optimizing coagulant dosage for drinking water treatment is essential for enhancing water quality. It also improves operational efficiency and cost-effectiveness. Traditionally, treatment plants focus on removing turbidity, often neglecting other critical factors such as co-pollutant removal, residual coagulant levels, and sludge production. This study addresses these limitations by optimizing coagulant dosage to simultaneously maximize turbidity and chemical oxygen demand (COD) removal, minimize residual Al concentrations, and reduce sludge generation. It employs a multi–parameter approach to improve the water treatment process, targeting low (10 NTU), medium (50 NTU), and high (400 NTU) turbidity synthetic water samples, representative of Mahaweli River water quality. The methodology includes preparing synthetic water, conducting jar tests to evaluate coagulation performance, and using design of experiments with Response Surface Methodology to identify optimal coagulant dosages and mixing speeds. Poly-aluminum chloride (PAC) was found to be the most effective coagulant for low- and medium-turbidity waters, with optimal dosages of 7 mg/l and 7.8 mg/l, and mixing speeds of 220 rpm and 216 rpm. Under these conditions, the final turbidity of water was 0.1648 NTU and 0.6890 NTU, with sludge weights of 0.0047 g and 0.0382 g, respectively. For high turbidity water, alum was optimal at 27 mg/l, with a mixing speed of 226 rpm, resulting in a turbidity of 2.3904 NTU and a sludge weight of 0.2203 g. COD removal percentages for low, medium, and high turbidity samples were 49.12%, 53.45%, and 49.57%. Residual aluminum levels remained below 10 ppm across all samples, measured via titration and Atomic Absorption Spectroscopy (AAS). These findings show that optimized coagulant dosage improves water quality, reduces sludge, and minimizes chemical residuals, providing cost-effective and sustainable improvements in water treatment. The study recommends multi–parameter optimization strategies and mechanical mixing methods in conventional water treatment plants to enhance efficiency and ensure high-quality drinking water.

Keywords: *COD, Design of Experiments, Optimization, Residual Coagulant, Turbidity*

1. Introduction

Water treatment is essential to ensure the availability of clean and safe drinking water for the public. Having a good quality water supply is a critical resource for public health. There are several unit processes to treat water in water treatment plants. Among them, coagulation is the widely used method. It removes suspended particles, colloids, and organic contaminants from the water. In the coagulation process, necessary chemical agents were added to the water, and subsequently, suspended particles and

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colloids in the water were destabilized and coagulated to form a large particle floc that could settle quickly [1].

Traditionally, most treatment plants use turbidity removal to optimize the coagulant dosage. The jar test is used as a laboratory-scale procedure to determine the appropriate coagulant dosage for maximum turbidity removal. However, this approach has some limitations. It only addresses a single parameter, and factors like sludge generation, residual coagulant concentration, and removal of natural organic matter are neglected. Natural organic matter (NOM) in water has adverse effects. Disinfection byproducts (DBPs) are one of the primary outcomes of NOM. These DBPs are identified as harmful chemicals to the human body. According to past studies, these agents have been identified as carcinogenic compounds [2]. Past studies identified that DBPs include aliphatic halogenated trihalomethanes (THMs), haloacetonitriles, and haloacetic acids (HAAs). These compounds cause various cancers, endocrine disorders, and numerous other diseases [3]. Due to these reasons, removing NOM from water during coagulation is crucial.

To address this challenge, the coagulant dosage optimization process must go beyond turbidity removal. Several studies were conducted to optimize coagulant dosage by considering NOM removal. Moreover, considering the past studies, the amount of NOM can be measured using COD [4]. Beyond optimizing the coagulant dosage by considering turbidity and COD removal, reducing sludge generation, and minimizing Al residuals have also become primary needs of the water treatment process. Sludge production depends on the type of coagulant and other suspended particles in the RAW water [5]. Recent studies discovered the possibility of recovering coagulants from sludge and minimizing waste [6]. Especially when coagulants like Alum and PAC are in use, the presence of residual Al in treated water will be high. Exposure to Al in treated water can lead to numerous human health problems [7]. Thus, optimizing the coagulant dosage in water treatment is a multifaceted problem that requires careful studies about turbidity removal, NOM removal, reducing sludge, and minimizing residual aluminum.

Response Surface Methodology (RSM) will be used as an optimization technique. RSM is the most commonly used optimization process for multi-factor optimization. RSM is a statistical and mathematical method that researchers can use to model the interactions between multiple responses [8]. Referring to previous studies, a considerable research gap exists in optimizing coagulant dosage by considering all these factors. So, this research aims to find a coagulant dosage that improves treatment efficiency, minimizes waste, minimizes residual aluminum at the end of the treatment process, and also improves the mixing mechanism of conventional treatment plants.

2. Materials and methods

2.1. Chemicals and instruments

Polly Aluminium Chloride (PAC) and Alum ($Al_2(SO_4)_3$) are used as coagulants. $MgSO_4.7H_2O$, $NaNO_3$, $CaCl_2$, NaOH, Kaolin Caly, and Glucose were used as materials in this research. All reagents except for kaolin clay and glucose were of analytical grade and obtained from the laboratory stock. Kaolin clay and glucose were procured from a local commercial supplier without specification of grade and used as received.

JLT 6 Leaching Test Jar Test machine was used for the jar tests. The HACH 2100N turbidity meter was used to measure the turbidity levels. For the COD measurements, the Titration method was used. The residual Al concentration was measured using a Thermo SOLAAR M series AAS, and the centrifugation was done TOMY Suprema 21 High Speed Refrigerated Centrifuge.

2.2. Preparation of synthetic wastewater

The synthetic water samples were designed to represent the water quality of the Mahaweli River, Sri Lanka's longest river and a primary source for drinking water treatment. Actual river characteristics were taken from recent studies, which reported turbidity levels ranging from 3-33 NTU across upstream catchments, with averages of 6.92 – 14.22 NTU depending on land use and minimal seasonal variations. The COD value in the upper section of the Mahaweli River is between 9 and 19 mg/l. The Electrical Conductivity (EC) value is between 67 and 133 μS/cm [9]. Higher turbidity is observed in urban–dominated downstream areas due to runoff and erosion. Some additional studies confirm low to moderate turbidity in the upper Mahaweli River [10]. Using these parameters, three synthetic water samples were prepared by varying the turbidity levels (10, 50, 400 NTU) using Kaolin Clay through a trial-and-error method, while keeping all other parameters, such as COD, EC, and pH, constant by adding glucose, $NaNO_3$, $CaCl_2$, and $MgSO_4.7H_2O$ to represent the actual river water characteristics. Table 1 shows the composition of the synthetic wastewater.

Table 1. Composition of the synthetic water

Ingredients	Concentration (mg/l)	Purpose
Kaolin Clay	40	Generate a low turbidity value for 1st sample set
	400	Generate the middle turbidity value for the 2nd sample set.
	1400	Generate a high turbidity value for the 3rd sample set.
Glucose	25	COD source
$NaNO_3$	3	Electrical conductivity adjustment
$MgSO_4$	9	
$CaCl_2$	32	
HCl / NaOH		pH adjustment

To represent the low turbidity level, 10 NTU water samples were prepared. It represents typical dry season conditions in the Mahaweli River, where turbidity averages 6 – 8 NTU [9,10]. To represent the medium-range turbidity water, 50 NTU water samples were prepared. It simulates moderate pollution or wet season runoff, aligning with observed peaks of 18 – 33 NTU in urban midstream sections of the Mahaweli River [11]. To represent high turbidity water, 400 NTU water samples were prepared. Due to factors like monsoons, floods, and high sediment loads, the turbidity can spike to more than 100 NTU [12].

2.3. Conducting Jar test

Six 500 ml beakers were used to set up the Jar test experiment, and these beakers were connected to a stirrer machine, as shown in Figure 1. Kaolin simulated wastewater was mixed after adding coagulant (PAC/Alum), rapid mixing for 5 min, and then slow mixing (40 rpm) for 30 min. The supernatant was collected after 45 45-minute settling time using a syringe [13]. And then measured using a turbidity meter. Settled sludge was separated by centrifugation [14].

Figure 1. Schematic diagram of the Jar test setup

2.4. Preliminary tests

The working range of the coagulant dosage and mixing speed was obtained by conducting preliminary tests. The results obtained from the jar test experiment showed that the Alum dosage between 4 and 20 mg/L, and PAC dosage between 4 and 10 mg/L for low turbidity water; Alum dosage between 12 and 20 mg/L, and PAC dosage between 6 and 10 mg/L for middle turbidity water; Alum dosage between 10 and 40 mg/L, and PAC dosage between 5 and 25 mg/L for high turbidity water. For all these sample types, the working range for mixing speed was 170 – 270 rpm.

2.5. Optimization of the coagulation process using the RSM approach

The Response Surface Methodology (RSM) was employed to address the limitations of traditional single-factor methods [15]. RSM allowed simultaneous optimization of coagulant dosage and mixing speed while considering their interactive effects. By using RSM, it is possible to minimize the experimental effort while simultaneously generating predictive models that support process optimization and design [1]. To optimize the coagulant dosage and mixing speed, a Central Composite Design (CCD) model based on two factors was used in MiniTab software. A total of 78 experiments were conducted, with 13 tests at each turbidity level with each coagulant type. For all these experiments, the final turbidity and generated sludge weight were measured. Using Analysis of Variance (ANOVA), the optimum dosages and mixing speeds were obtained considering only turbidity removal and sludge generation.

2.6. COD removal efficiency and residual Al concentration

The titration method was used to measure the COD concentration, and residual Al concentration was measured using an Atomic Absorption Spectroscopy (AAS) machine. COD removal efficiency was calculated using Equation 1. The initial COD value of the water and the COD value of the treated water are represented by C_i and C_f.

$$\text{COD removal efficiency} = (C_i - C_f)/C_i \times 100\% \quad (1)$$

2.7. Validation with actual river water

The optimal dosage and mixing speed obtained from the analysis were verified using actual river water. For this validation, water samples were collected from the intake of the Kandy-South Water Treatment Plant. First, measure pH, electrical conductivity, initial turbidity, and initial COD concentration. Then, a jar test was performed by adding the optimal dosage at the optimal mixing speed. The final turbidity and COD concentrations of the treated water were then measured.

3. Results and discussion

3.1. Preliminary experimental results

Thirteen preliminary experiments were conducted to observe the coagulation process and determine the appropriate range for coagulation dosage and mixing speed. These experiments covered three turbidity ranges. From these results, the working ranges of Alum dosage and mixing speed for low, middle, and high turbidity water were identified. These ranges are shown in Table 2.

Table 2. Level values for RSM test design

Turbidity Level	Coagulant Type	Parameter	Low Value (-1)	High Value (+1)
Low	Alum	Coagulant dosage (mg/L)	4	20
		Mixing Speed (rpm)	170	270
	PAC	Coagulant dosage (mg/L)	4	10
		Mixing Speed (rpm)	170	270
Middle	Alum	Coagulant dosage (mg/L)	12	20
		Mixing Speed (rpm)	170	270
	PAC	Coagulant dosage (mg/L)	6	10
		Mixing Speed (rpm)	170	270
High	Alum	Coagulant dosage (mg/L)	10	40
		Mixing Speed (rpm)	170	270
	PAC	Coagulant dosage (mg/L)	5	25
		Mixing Speed (rpm)	170	270

3.2. Effect of coagulant dosage and mixing speed on turbidity removal and sludge generation

The study aimed to optimize the coagulant process for water treatment across low, middle, and high turbidity levels using Alum and Poly Aluminum Chloride (PAC). The Design of Experiments (DOE) method was used to identify the optimal conditions for minimizing final turbidity and sludge production. Six sets of experiments were conducted with three different water samples (low turbidity sample, middle turbidity sample, and high turbidity sample) and two types of coagulants (PAC and Alum).

3.2.1. Low turbidity water

For low turbidity water, PAC was the most effective coagulant, achieving optimal conditions at a dosage of 7 mg/L and a mixing speed of 220 rpm. Usually, PAC is known to form strong electrostatic patch flocs that are particularly effective in water with low particulate concentrations. These flocs enhance charge neutralization and bridging mechanisms, which are critical in achieving effective coagulation in low turbidity waters [16]. In addition, PAC exhibits superior performance at lower dosages compared to Alum, particularly in waters with low turbidity and low natural organic matter (NOM) content [17]. PAC produced larger and more settleable flocs with lower residual turbidity and sludge volumes, which is beneficial in terms of both treatment efficiency and operational costs [18]. These findings are consistent with the present study, where PAC demonstrated both lower sludge generation and lower optimal dosage requirements while still meeting water quality standards. These combined results achieved the final turbidity below the standard of 2 NTU and at a minimum sludge generation. These results can be discussed further using the ANOVA. Tables 3 and 4 illustrate the ANOVA results for the RSM on final turbidity and sludge generation for low turbidity water with PAC.

Table 3. ANOVA table for final turbidity with PAC for low turbidity water

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	11.0932	2.21865	4.01	0.049
Linear	2	0.9936	0.49681	0.90	0.449
Dosage	1	0.0089	0.00889	0.02	0.903
Speed	1	0.9847	0.98474	1.78	0.224
Square	2	9.9627	4.98136	9.01	0.012
Dosage*Dosage	1	1.7467	1.74670	3.16	0.119
Speed*Speed	1	9.0858	9.08576	16.43	0.005
2-Way Interaction	1	0.1369	0.13690	0.25	0.634
Dosage*Speed	1	0.1369	0.13690	0.25	0.634
Error	7	3.8709	0.55298		
Lack-of-Fit	3	3.8708	1.29027	115202.57	0.000
Pure Error	4	0.0000	0.00001		
Total	12	14.9641			

Table 4. ANOVA table for sludge generation with PAC for low turbidity water

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	11.0932	2.21865	4.01	0.049
Linear	2	0.9936	0.49681	0.90	0.449
Dosage	1	0.0089	0.00889	0.02	0.903
Speed	1	0.9847	0.98474	1.78	0.224
Square	2	9.9627	4.98136	9.01	0.012
Dosage*Dosage	1	1.7467	1.74670	3.16	0.119
Speed*Speed	1	9.0858	9.08576	16.43	0.005
2-Way Interaction	1	0.1369	0.13690	0.25	0.634
Dosage*Speed	1	0.1369	0.13690	0.25	0.634
Error	7	3.8709	0.55298		
Lack-of-Fit	3	3.8708	1.29027	115202.57	0.000
Pure Error	4	0.0000	0.00001		
Total	12	14.9641			

The P value and F value of the model were 0.049 and 4.01. This indicates that the overall model is marginally significant, suggesting it adequately captures the relationship between the factors and response. The linear terms were not significant because the p-value is 0.449, but the quadratic terms were significant because the p-value and the f-values are 0.012 and 0.449. For the speed-squared term, the p-value was 0.005. And this highlights the non-linear effect of mixing speed on turbidity removal. The interaction term was not significant because the p-value was 0.634. However, the lack of fit was significant, which may indicate that the model could be improved with additional factors or higherorder terms, though the low pure error suggests high experimental reproducibility. The regression equation for final turbidity is shown in Equation 2.

$$Final\ Turbidity\ (NTU) = 24.74 - 0.519\ Dosage - 0.1995\ Speed + 0.0557\ Dosage^2 + 0.000457 Speed^2 - 0.00123\ (Dosage\ \times Speed) \quad (2)$$

Similarly, the ANOVA for sludge weight shows the model is also marginally significant, because the F value and the p value are 4.02 and 0.049. The linear terms were insignificant since the p value was 0.501, but the quadratic terms were significant with a p value of 0.011 and a 9.27 F value. And the dosage squared term has a p-value of 0.007, and the speed squared term has a p-value of 0.043. This indicates that the curvature in the response surface is primarily dosage effects. The interaction was negligible, and the lack of fit was again significant because the p-value is 0.000. This happens due to unmodeled variability, but the model still provides useful insights for optimization. The regression equation for final turbidity is shown in Equation 3.

$$Sludge\ Genration\ (g) = 0.0734 - 0.00654\ Dosage - 0.000440\ Speed + 0.000442\ Dosage^2 + 0.000001\ Speed^2 + 0.000442\ (Dosage\ \times Speed) \quad (3)$$

These ANOVA results confirm the importance of quadratic effects in both responses, justifying the use of RSM for capturing non-linear interactions and enabling the identification of optimal conditions. The overlay contour plots for low turbidity with PAC in Figure 2 illustrate the relationship between coagulant dosage, mixing speed, final turbidity, and sludge generation.

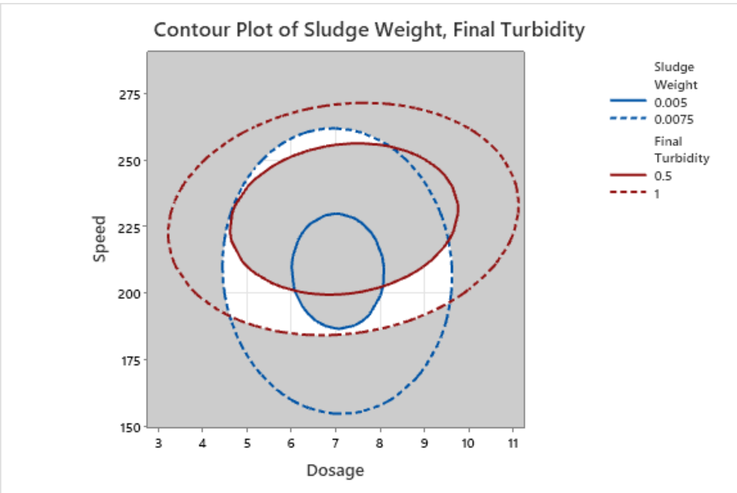

Figure 2. Overlay contour plots for final turbidity and sludge at low turbidity water with PAC

3.2.2. Middle turbidity water

For middle turbidity water, PAC was selected as the perfect coagulant due to its slightly better performance in achieving low turbidity and reduced sludge compared to Alum. According to the overlay contour plots, the optimum PAC dosage was 7.8 mg/L, and the mixing speed was 216 rpm. PAC, due to its high polymeric content and pre-hydrolyzed nature, can form larger flocs, which may settle faster but may also contribute to slightly increased sludge volumes under certain conditions. Additionally, it was observed that the optimum mixing speed required for Alum was higher than that for PAC, indicating the need for stronger mixing to achieve efficient coagulation with Alum [4]. Usually, Alum often requires higher energy input during the rapid mixing phase due to its dependence on in-situ hydrolysis and particle destabilization [17]. In contrast, PAC requires lower mixing energy due to its pre-formed polymeric species, which react more quickly and efficiently with colloidal particles. The ANOVA for final turbidity and sludge generation for middle turbidity with PAC is shown in Tables 5 and 6.

Table 5. ANOVA table for final turbidity with PAC for middle turbidity water

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	5	150.280	30.056	4.20	0.044
Linear	2	14.235	7.118	0.99	0.417
Dosage	1	1.611	1.611	0.22	0.650
Speed	1	12.624	12.624	1.76	0.226
Square	2	135.900	67.950	9.48	0.010
Dosage*Dosage	1	29.898	29.898	4.17	0.080
Speed*Speed	1	119.268	119.268	16.65	0.005
2-Way Interaction	1	0.144	0.144	0.02	0.891
Dosage*Speed	1	0.144	0.144	0.02	0.891
Error	7	50.150	7.164		
Lack-of-Fit	3	50.071	16.690	845.08	0.000
Pure Error	4	0.079	0.020		
Total	12	200.430			

Table 6. ANOVA table for sludge generation with PAC for middle turbidity water

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	5	0.001316	0.000263	5.71	0.020
Linear	2	0.000007	0.000003	0.07	0.931
Dosage	1	0.000007	0.000007	0.15	0.715
Speed	1	0.000000	0.000000	0.00	0.993
Square	2	0.001246	0.000623	13.53	0.004
Dosage*Dosage	1	0.000796	0.000796	17.28	0.004
Speed*Speed	1	0.000611	0.000611	13.26	0.008
2-Way Interaction	1	0.000063	0.000063	1.37	0.280
Dosage*Speed	1	0.000063	0.000063	1.37	0.280
Error	7	0.000322	0.000046		
Lack-of-Fit	3	0.000322	0.000107	4884.65	0.000
Pure Error	4	0.000000	0.000000		
Total	12	0.001639			

The ANOVA for final turbidity shows the model is significant (F = 4.20 and p = 0.044), with quadratic terms dominant (F = 9.48 and p = 0.010). The speed squared term (p = 0.005). Linear and interaction terms were insignificant in the model. The regression equation for Final Turbidity is shown in Equation 4.

$$Final\ Turbidity\ (NTU) = 103.4 - 7.65\ Dosage - 0.688\ Speed + 0.518\ Dosage^2 + 0.001656\ Speed^2 + 0.000040\ (Dosage\ \times Speed) \quad (4)$$

According to the ANOVA results on sludge generation, the model is significant with an F value of 5.71 and a p-value of 0.020, driven by quadratic effects (F=13.53, p = 0.004), with both dosage squared (p = 0.004) and speed squared (p = 0.008) notable. The regression equation for sludge weight is shown in Equation 5.

$$Sludge\ Genration\ (g) = 0.4570 - 0.0511\ Dosage - 0.001967\ Speed + 0.002674\ Dosage^2 + 0.000004\ Speed^2 + 0.000004(Dosage \times Speed) \quad (5)$$

Figure 3 illustrates the overlay contour plots final turbidity and sludge at the middle turbidity water with PAC.

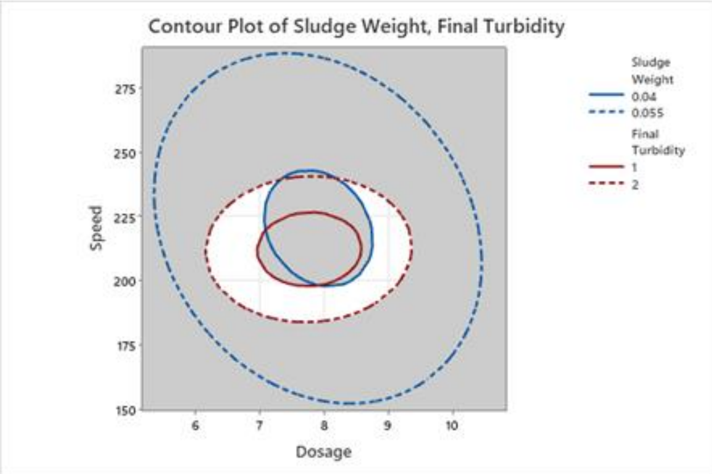

Figure 3. Overlay contour plots for final turbidity and sludge at low turbidity water with PAC

3.2.3. High turbidity water

According to the results of the jar tests conducted on high turbidity water, alum performed more effectively than PAC in terms of maximizing turbidity removal and minimizing sludge generation. While PAC demonstrated good performance in low and medium turbidity ranges, its efficiency decreased under high turbidity conditions. This observation can be attributed to the coagulation mechanisms of the two coagulants. Alum, upon hydrolysis, forms voluminous $Al(OH)_3$ precipitates that promote sweep flocculation, an ideal mechanism when dealing with high concentrations of suspended particles. The large quantity of particulate matter in high turbidity water enhances the settling efficiency of these flocs [19]. In contrast, PAC primarily relies on charge neutralization and polymeric bridging, mechanisms that are more efficient at lower particle concentrations [16]. In this study for high turbidity water, Alum outperformed PAC, with an optimal dosage of 27 mg/L and a mixing speed of 226 rpm. The ANOVA tables for final turbidity and sludge generation with Alum for high turbidity water are shown in Tables 7 and 8.

Table 7. ANOVA table for final turbidity with Alum for high turbidity water

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	620.998	124.200	9.43	0.005
Linear	2	63.554	31.777	2.41	0.160
Dosage	1	1.625	1.625	0.12	0.736
Speed	1	61.930	61.930	4.70	0.067
Square	2	556.443	278.222	21.12	0.001
Dosage*Dosage	1	521.709	521.709	39.60	0.000
Speed*Speed	1	77.837	77.837	5.91	0.045
2-Way Interaction	1	1.000	1.000	0.08	0.791
Dosage*Speed	1	1.000	1.000	0.08	0.791
Error	7	92.222	13.175		
Lack-of-Fit	3	92.021	30.674	609.21	0.000
Pure Error	4	0.201	0.050		
Total	12	713.220			

Table 8. ANOVA table for sludge generation with Alum for high turbidity water

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.049037	0.009807	4.77	0.032
Linear	2	0.009961	0.004981	2.42	0.159
Dosage	1	0.009915	0.009915	4.82	0.064
Speed	1	0.000046	0.000046	0.02	0.885
Square	2	0.039074	0.019537	9.50	0.010
Dosage*Dosage	1	0.020530	0.020530	9.98	0.016
Speed*Speed	1	0.023624	0.023624	11.48	0.012
2-Way Interaction	1	0.000002	0.000002	0.00	0.978
Dosage*Speed	1	0.000002	0.000002	0.00	0.978
Error	7	0.014403	0.002058		
Lack-of-Fit	3	0.014403	0.004801	120023.59	0.000
Pure Error	4	0.000000	0.000000		
Total	12	0.063440			

The ANOVA for final turbidity indicates a significant model with a p-value of 0.005 and F F-value of 9.43. And it is primarily driven by quadratic terms (F = 21.12, p = 0.001), with the dosage squared term highly significant and the speed squared term notable (p = 0.045). The linear and interaction effects were insignificant. The regression equation for final turbidity is shown in Equation 6.

$$Final\ Turbidity\ (NTU) = 99.1 - 1.748\ Dosage - 0.628\ Speed + 0.03849\ Dosage^2 + 0.001338\ Speed^2 - 0.00067\ (Dosage\ \times Speed) \quad (6)$$

For the sludge generation, the model is significant with a p-value of 0.032 and an F value of 4.77. The quadratic effects are prominent with an F value of 9.50 and a p value of 0.010, including dosage squared (p = 0.016) and speed squared (p =0.012). The regression equation for sludge generation is shown in Equation 7.

$$Sludge\ Generation\ (g) = 1.555 - 0.01461\ Dosage - 0.01023\ Speed + 0.000241\ Dosage^2 + 0.000023\ Speed^2 + 0.000001(Dosage\ \times Speed) \quad (7)$$

Figure 4 illustrates the overlay contour plots for the final turbidity and sludge generation in high turbidity water with Alum.

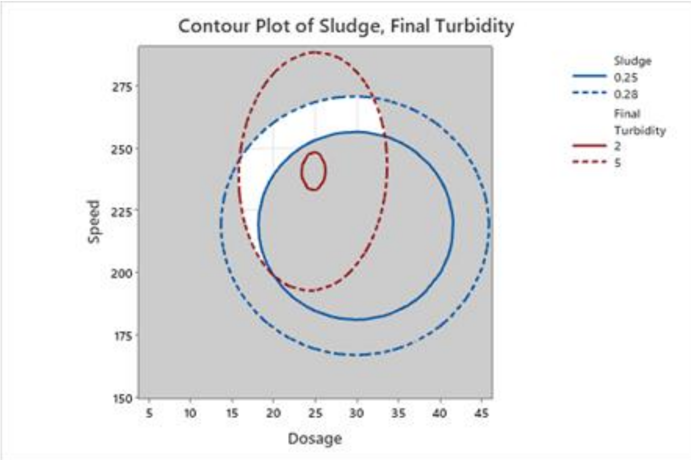

Figure 4. Overlay contour plots for final turbidity and sludge at high turbidity water with Alum

3.3. Comparison of COD removal efficiency and residual Al concentration

According to the six optimization analyses, two samples from each working range were selected for further analysis to determine the COD removal efficiency and Residual Al concentrations. According to the results, PAC exhibited slightly better COD removal in low and medium turbidity ranges, which aligns with literature suggesting PAC's superior performance in reducing organic content due to its pre-hydrolyzed polymeric structure and enhanced charge neutralization capabilities [4]. Table 9 illustrates the summary of results for COD removal efficiency and Residual Aluminum Concentration.

Table 9. COD removal efficacy and residual Al concentration of treated water

Turbidity Level	Coagulant Type	Dosage (mg/L)	Speed (rpm)	COD Removal efficiency (%)	Al concentration (ppm)
Low	PAC	7	220	49.12	Below the detection limit of 10 ppm
Low	PAC	4	170	23.01	
Middle	PAC	8	220	53.45	
Middle	PAC	6	170	55.24	
High	Alum	25	220	49.57	
High	Alum	40	270	49.87	

3.4. Validation of optimum dosage and mixing speed

Water samples from the upper catchment area of the Mahaweli River were collected at the intake of the Kandy South Water Treatment Plant. The initial turbidity of water was 4.83 NTU. So, the water type is identified as low turbidity water, and the coagulation process was done according to the results obtained for low turbidity water with PAC. Table 10 illustrates the water quality parameters of the treated water.

Table 10. Treated water quality parameters of the river water

Parameter	Value
Turbidity (NTU)	0.833
COD (mg/L)	8.4
Sludge Weight	0.0090
Residual Al (ppm)	Below the detention limit of 10 ppm

4. Conclusion

This research investigated optimal coagulant dosages for water treatment, focusing on maximizing co-pollutant removal while minimizing residual coagulant and reducing sludge generation across different turbidity levels. The novelty of this study, compared to traditional jar test studies, which evaluate Al–based coagulants primarily for turbidity removal using response surface analysis for predicting optimal dosages with a focus on a single parameter like coagulation dosage, this study focused on a multi-parameter approach to predict the coagulation dosage. Experiments used synthetic water to represent Mahaweli River water with low (10 NTU), medium (50 NTU), and high (400 NTU) turbidity. For low and medium turbidity, poly aluminum chloride (PAC) was most effective, with optimal dosages of 7 mg/L (220 rpm mixing speed) and 7.8 mg/L (216 rpm), achieving final turbidities of 0.1648 NTU and 0.6890 NTU, and sludge weights of 0.0047 g and 0.0382 g, respectively. For high-turbidity water, Alum was optimal at 27 mg/L (226 rpm), yielding 2.3904 NTU and 0.2203 g sludge. COD removal efficiencies were 49.12%, 53.45%, and 49.57% for low, medium, and high turbidity, respectively, with residual aluminum below 10 ppm. Validation using Mahaweli River water (below 10 NTU) with low-turbidity settings resulted in 0.833 NTU and 86% COD removal. The study highlights that optimizing coagulant dosage and mixing speed enhances water quality, reduces costs, and supports effective treatment techniques. Additionally, targeting Mahaweli River-specific turbidities (10-400 NTU) with synthetic samples and validating on actual river water bridges lab-scale to practical application, recommending mechanical mixing for enhanced efficiency in Sri Lankan treatment plants. The study also recommends using a more sensitive method (0.1 ppm detection limit) for residual aluminum, adopting cost-effective COD measurement methods, and further studying Alum's effectiveness for high-turbidity water to validate its preference over PAC. The health risks of DBPs such as THMs and HAAs are formed when residual natural organic matter reacts with disinfectants like chlorine, leading to cancers and endocrine disruption. This study did not directly measure these compounds, as the focus was on optimizing the coagulation stage upstream of disinfection. Instead, COD removal efficiency was evaluated as a surrogate for NOM reduction, which mitigates DBP precursor levels. Residual aluminum was also monitored to ensure no additional health risks from coagulants. Future work could extend this to post-disinfection analysis to quantify DBP formation under optimized conditions.

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Conflict of Interest

We declare no conflict regarding the publication of the study.

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