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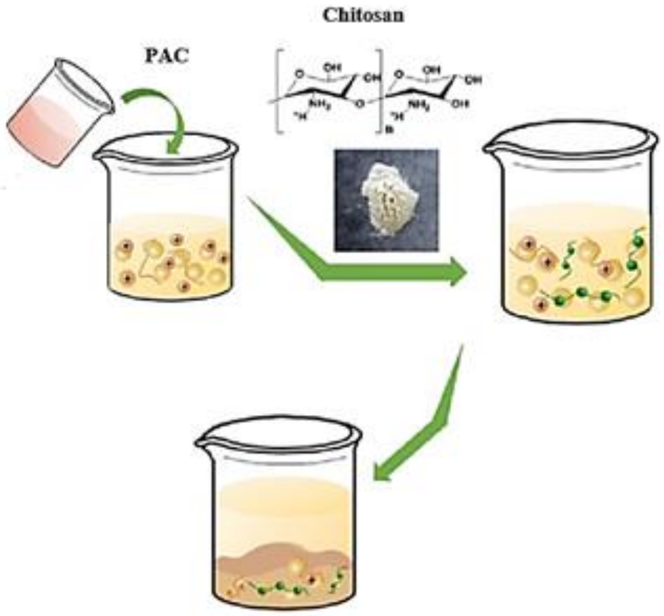
Experimental study of polyaluminum chloride-chitosan coagulant for water treatment using response surface methodology

Mohammad Yousefi[1], Ehsan Jabbari[1], Mehdi Sedighi*[,2]

[1]Department of Civil Engineering, Faculty of Engineering, University of Qom, Qom, Iran.
[2]Department of Chemical Engineering, Faculty of Engineering, University of Qom, Qom, Iran.

GRAPHICAL ABSTRACT



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ABSTRACT

Water shortages and pollution are so severe that the last decade has been called the international decade for water. In water treatment plants, coagulation and flocculation are used to remove turbidity. This study examined the use of natural coagulants and its efficiency compared with existing coagulants. Response surface methodology was used to design the experiments. Type of coagulant and coagulant aid, as well as pH, were considered important factors during experiments. Results of the tests indicate that pH has a significant impact on turbidity removal. The combination of chitosan and polyaluminum chlirode reduces water turbidity effectively. A combination of polyaluminum chlirode (7.6 mg/L) and chitosan (9.28 mg/L) at pH= 8.52 removed 99.85 % of the turbidity. Accordingly, the combined use of polyaluminum chlirode and chitosan reduced the amount of material and enhanced turbidity removal.

1. Introduction

All forms of life rely on water for survival (Shamshiri et al. 2020). Growing populations and diverse industries have steadily increased the demand for high-quality, safe drinking water globally. Contaminated water is a significant environmental issue since water is necessary for all life forms (Alimohammadi et al. 2021; Sedighi and Mohammadi. 2018). Wastewater treatment aims to protect the environment and reduce freshwater consumption by industries (Alimohammadi and Sedighi 2018; Samari et al. 2020; Shahveh et al. 2020). Conventional technologies, such as adsorption (Alimohammadi et al. 2017; Mohammadi et al. 2021; Mohammadi et al. 2019), sedimentation, and filtration (Oulad et al. 2018; Sedighi et al. 2020), have been frequently applied to treat these water supplies in the past. The conventional

*Corresponding author Email: sedighi@qom.ac.ir

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methods, however, cannot remove turbidity due to several weaknesses. The conventional treatment of water relies heavily on coagulation and flocculation (Setareh et al. 2020).

In conventional water treatment plants, drinking water is purified using coagulation, a well-established physicochemical technique (Xiao et al. 2009). Coagulation performance is affected by raw water characteristics in practice (Naveed et al. 2021; Ng et al. 2013; Xiao et al. 2009; Yu et al. 2007). The treatment of low turbidity and low temperature contaminated water is complex because the low temperature and low turbidity adversely affect the hydrolysis of metals (e.g., Al and Fe), particle aggregation, and floc structure (Huang et al. 2015; Xiao et al. 2008). Water and wastewater treatments frequently use chemical coagulants, such as inorganic substances (aluminum and iron) and synthetic organic polymers and biopolymers, since these substances are inexpensive and straightforward (Sillanpää et al. 2018; Tran et al. 2020). The use of chemical coagulants and flocculants in studies has ranged from iron salts (Jiang and Lloyd. 2002), to modified clays and ferromagnetic nanoparticle composites (Zhang et al. 2012), to polyaluminum chloride-coated magnetic beads (PAC) (Wu et al. 2020). Some chemicals used as coagulants can be toxic and negatively contribute to human and environmental health. Alzheimer's disease, cognitive impairment, and neurological disorders are among the diseases caused by aluminum sulphate (Rao 2015; Tran et al. 2020). The disposal of chemical residues could result in higher disposal costs due to their non-biodegradability and toxicity. Compounds/polymers based on aluminum, like polymeric aluminum, are widely used as coagulants to remove particles from raw water (Jiao et al. 2015). To increase flocculation/coagulation performance, polymeric coagulant aids should be used to remove high turbidity (Al-Juboori et al. 2016; Yan et al. 2008) particularly in low-turbid waters (Setareh et al. 2020). PAC, a pre-hydrolyzed aluminum-based polymer coagulant, can work more effectively at lower temperatures because it is less sensitive to temperature changes than other polymers (Renault et al. 2009). In low-temperature, low-turbidity water, a high concentration of PAC is still required to achieve satisfactory coagulation results (Cheng et al. 2008; Xiao et al. 2009). In excess of PAC, residual Al can easily increase, which is harmful, since high residual Al concentrations can lead to turbidity due to the formation of Al precipitates and may even cause neurological damage (Xiao et al. 2008). In this regard, improving coagulation efficiency while minimizing residual Al content is a crucial factor that needs to be addressed, especially for raw water with low temperature and low turbidity.

A critical parameter that can influence PAC properties and subsequent coagulation performance is its basicity (Lei et al. 2009). Coagulation pH is an important factor that affects the enhanced coagulation. The adjustment of pH is an important way to enhance removal efficiency in coagulation units, and in this process, the floc size, strength and structure can be changed, influencing the subsequent solid/liquid separation effect. The size of the coagulated particles is also affected by pH, which, in turn, determines the density of the flocculated slime and its tendency and rate of settling out. Several investigations have studied the influence of PAC basicity on coagulation, but the results have been inconsistent. Coagulation efficiency can be improved when PAC is used with a high basicity value (McCurdy et al. 2004; Shirasaki et al. 2014). PACs with low basicity were more efficient for coagulation in other cases (Yan et al. 2008; Yang et al. 2011). Therefore, coagulation performance of PACs with various basicities should be examined in the treatment of water with specific characteristics, for example, raw water with a low temperature and low turbidity. A close relationship exists between PAC's basicity and the residual Al content (Kimura et al. 2013). Consequently, adjusting basicity may be an appropriate approach for increasing coagulation performance and reducing residual Al concentrations. When PAC is used as the primary coagulant, coagulation aids are often required to ensure low residual aluminum levels in water and improve coagulation efficiency (Hu and Wu 2016; Zhang et al. 2018).

By using coagulants derived from plants or polysaccharides obtained from bacteria, these problems can be addressed, and nutrient-rich sludge can be produced and reused (Tran et al. 2020). Nirmali seeds, Moringa oleifera seeds, Opuntia ficus-indica cactus and tannin are all plant-based natural coagulants that can treat water and wastewater (Choy et al. 2015; Choy et al. 2014). Furthermore, alginates and chitosan are considered popular green coagulants for coagulation-flocculation. (Tran et al. 2020). In recent decades, chitosan has been recommended as a coagulant aid in water treatment (Renault et al. 2009; Roussy et al. 2005). Biodegradable and non-toxic, chitosan is effective as a natural coagulant and flocculant in treatment (Sahoo et al. 2009). Chitosan can also eliminate color from synthetic dye wastewater (Sakkayawong et al. 2005), as well as heavy metal ions (Ngah et al. 2011), particularly in nutrient-rich wastewater. Even though chitosan has a lower quality than those typically used as coagulants, it is still predicted to be effective in wastewater treatment, which has yet to be tested (Tran et al. 2020). Chitosan along with an Al-based salt/polymer has previously been demonstrated to be effective at eliminating turbidity. Further, using PAC alone as a coagulant results in much lower residual Al concentrations (Hu et al. 2013).

To date, the combination of PAC and chitosan has not been thoroughly tested for increasing coagulation efficiency or reducing residual Al levels, particularly in water with low temperatures and low turbidity. As a result, the objectives of this study are: (i) to examine the influence of various PAC basicities on coagulation efficiency and residual Al levels; (ii) to determine the effectiveness of a PAC with chitosan for treating low temperature and low turbidity water; and (iii) to clarify the mechanisms used for removing turbidity using PAC and chitosan.

2. Materials and methods

The chemicals used in this study were ferric chloride [$FeCl_3.6H_2O$], alum [$Al_2(SO_4)_3.18H_2O$], poly aluminum chloride (PAC, [$Al_2(OH)$ n-Cl_6-n.YH_2O]Z), H_2SO_4 (0.02 N), H_3PO_4, formazin, potassium indigotrisulfonate, sodium dihydrogen phosphate (Sigma Company), platinum cobalt color reference solution (Merck, Darmstadt, Germany), , sodium salt of humic acid (Aldrich) and coagulants aid. Deionized distilled water (DDW) was utilized to prepare the chemical solutions and stocks used in this study. The PAC stock solution was obtained at a concentration of 50 g/L in water. After stirring (100 rpm) at room temperature for 5 min, it dissolved completely. The polyacrylic acid (PAA) stock solution was prepared at 5 g/L in water. After stirring (100 rpm) for 2 h at room temperature, PAA was completely dissolved. Chitosan stock solution was prepared at 10 g/L in 1% aqueous acetic acid. Chitosan is a natural polysaccharide commonly present in significant levels and has particular features that can't be found in synthetic polymers. Chitosan is a linear polysaccharide containing randomly distributed *β*-(1→4)-linked d-glucosamine and *N*-acetyl-d-glucosamine after deacetylated from chitin. The chemical structure of chitosan is shown in Fig. 1.

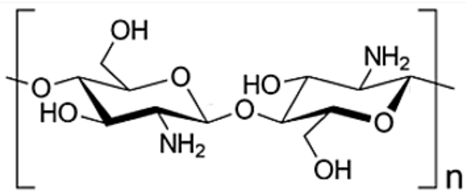


Fig. 1. Chemical structure of chitosan.

All coagulation and flocculation (jar test) experiments were conducted with a six-unit combined mixer (JLT6, LOVIBOND, Dortmund, Germany). Jar test is a pilot-scale laboratory test that simulates coagulation or flocculation with differing chemical doses. The purpose of the jar test is to estimate the minimum coagulant dose required to achieve certain water quality goals. Jar test helps to determine the right amount of treatment chemicals. Using a flocculator, the coagulant substance is added to the water sample beakers. The chemical coagulant starts to precipitate trapping all the impurities and forming flocs that will deposit on the bottom of the beaker. The sample is continuously stirred so that the formation, development, and settlement of floc can be observed just as it would occur in the full-scale water treatment plant. Then a series of tests were performed to compare the effects of different amounts of flocculation agents at different pH values to determine the right size floc. The analytical conditions are: 1000 ml glass beakers (jars), tall form, Ø 105 mm, 600 ml wastewater samples + coagulant, Height of paddles: middle height of the sample, turbulent stirring: 120 rpm, 120 seconds, Slow speed flocculation: 30 rpm, 25 min, first evaluation of results after 5 min of sedimentation. The wastewater quality parameters are measured (Table 1).

Table 1. Physical-chemical analysis for wastewater characterization.

Parameter	Range	Unit
pH	7-7.5	-
Turbidity	350-600	NTU
Hardness	160-210	mg/L as $CaCO_3$
Alkalinity	190-230	mg/L as $CaCO_3$
MPN	2500-35000	Nos./100 m

2.1. Characterization techniques

The scanning electron microscope (Model: Hitachi SU Series, Japan) was used for the morphological study of the samples with a magnification of 10.0 KX, working distance (WD) of 20 mm, secondary electrode 1 (SE 1) detector, and EHT of 10 kV. Crystalline structure and phase analysis were examined using X-ray Diffractometer (XRD, Bruker D8) using CuKa radiation (40 kV and 50 mA). A Nicolet 370 spectrophotometer was used to perform diffuse reflectance FTIR. FTIR experiments were conducted on pure powder samples without KBr under nitrogen flow on in-situ heat-treated samples.

3. Results and discussion

3.1. Physicochemical characterization

Fig. 2a & b illustrates SEM images of the samples. A nonporous, smooth membranous phase of chitosan was observed in the SEM images, consisting of dome-shaped orifices, crystallites, and microfibrils. The crystal granules out of order on the end surface of PAC accumulated along a straight level, as shown in Fig. 2b. The Fig. 2c shows XRD patterns of the samples. Chitosan exhibits vast peaks at 2θ = 15.2° and 20.2°. These crystalline peaks can be attributed to the (110) and (220) reflection planes (Aziz et al. 2017). Recent studies have revealed that intramolecular and intermolecular hydrogen bonds support chitosan's rigid crystalline structure and determined the average intermolecular distance between the crystalline parts (Aziz and Abidin 2013). A broad peak at 2θ ranges from 35 to 55 relates to the amorphous region of chitosan (Belamie et al. 1999). CaF_2 and $CaSiF_6$ and $AlCl_3$ were detected in the XRD spectra of PAC generated from polymerization induced by calcium aluminate. The reason is that HF dissolved SiO_2 in calcium aluminate to form SiO_3^{2-}, and both SiO_3^{2-} and F^- react with Ca^{2+} leached from calcium aluminate to form water-insoluble CaF_2 and $CaSiF_6$. Fig. 2d presents the FTIR spectra of samples. The chitosan spectrum shows several characteristic peaks at 3510 cm^{-1} (O–H group), 3050 cm^{-1} (C–H stretch), 2984 cm^{-1} (C–H stretch), 1490 cm^{-1} (C=C stretch of aromatic ring) (dos Santos et al. 2005). For the PAC sample, a broad absorption peak at 3430 cm^{-1} could be due to the stretching vibrations of OH groups. The peaks at 1592 cm^{-1} were assigned to the bending vibrations of water absorbed, polymerized, and crystallized in the coagulant. The peak at 992 cm^{-1} was due to the asymmetric stretching vibration of Fe–OH–Fe or Al–OH–Al. In addition, two peaks were observed at 690 cm^{-1} and 645 cm^{-1} attributed to bending vibrations of Fe–OH and Al–OH, respectively (Varma and Sugumar. 2020).

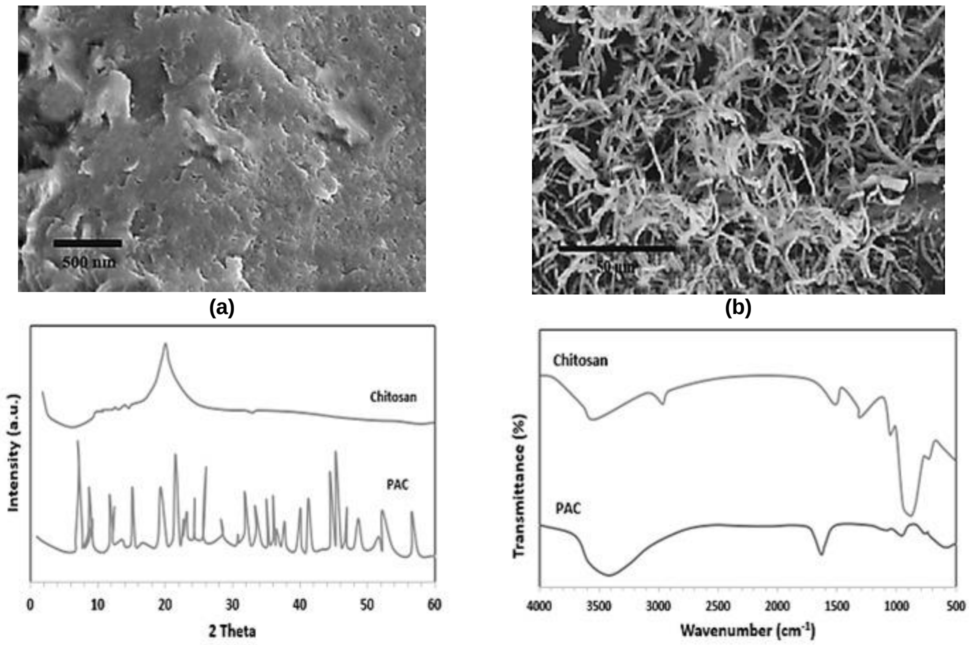
3.2. Experimental design

Response surface methodology (RSM) uses mathematical and statistical methods to evaluate the significance of effective parameters (Abdolmohammad-Zadeh et al. 2013,. Mohammadi et al. 2021). The experimental design was performed using RSM and CCD (Mohammadi et al. 2018,. Sedighi et al. 2018). The experiments were conducted at different pH levels and coagulant doses based on a central composite method with circumscribed types. Based on the factors considered and the desired repeatability, the experimental points are chosen at a distance α from the central point. For three repeats of two factors (k=2) at the center position, 12 experiments (N) are required. There are 18 experiments for three factors (k = 3).

The value of α is calculated as 1.414 for k = 2 and 1.353 for k = 3. The experiments used 500 mL samples of wastewater in six beakers. The pH value of each sample was adjusted based on the experimental design. The range of pH values ranged from 4 to 10. During the first two minutes of all experiments, different coagulant solutions were added under stirring at 150 rpm at room temperature. At a stirring speed of 20 rpm, the flocculation took 15 min. After 30 min, the samples were settled and the turbidity of the supernatant liquid was measured. Chitosan optimization experiments were performed using the Central Composite Design (CCD) (Nouri et al. 2013). The experimental procedure was identical to that described above.

Table 2. Coded levels and factors for CCD study.

Level	Chitosan dose (A)	pH (B)
-*α*	10.00	2.00
-1	13.66	3.17
0	22.50	6.00
+1	31.34	8.83
+*α*	35.00	10.00



(a) (b) (c) (d)

Fig. 2. (a) SEM image of chitosan, (b) SEM image of PAC, (c) XRD pattern and (d) FT-IR spectra.

3.3 Coagulation results by chitosan

The coded levels and factors for chitosan are defined in Table 2. Two independent variables, chitosan consumption, and initial pH, were analyzed in 10-35 ranges and 2-10 ranges, respectively. Additionally, the rate of turbidity removal was considered as a response variable. Table 3 illustrates the Matrix design of the experiment and removal results. According to the experimental results, the equation for the constructed model will be as follows:

$$\text{Turbidity removal (\%)} = 70.12-1.15A+12.65B+0.32AB+7.44A^2+7.44B^2 \quad (1)$$

where, A and B are the chitosan dose and pH, respectively. In order to assess the effects of chitosan use and pH on turbidity removal percentage, a 3D diagram of the model was drawn, and these two parameters were examined, as shown in Fig. 3. On the basis of the above diagram, pH increases turbidity removal percentage. Low and high doses of chitosan have a greater impact on turbidity removal percentage than average doses. Accordingly, pH significantly influences turbidity removal percentage, but the impact of chitosan is unclear. A higher pH value and a lower dose of chitosan resulted in the highest removal percentages. To achieve optimization, two independent variables (chitosan dose and pH) have been considered within the range determined as the basics of design. In contrast, the independent variable (turbidity removal percentage) has been set to result in the most significant percentage of turbidity removal. The results of the optimization process are shown in Table 4.

Table 3. Matrix design for the effective factors for turbidity removal using chitosan.

Run no.	Parameters		Turbidity removal, %
	pH	Chitosan dose, mg//L	
1	6.00	22.50	62.80
2	6.00	22.50	71.75
3	6.00	35.00	62.68
4	8.83	31.34	99.58
5	6.00	22.50	70.63
6	3.17	31.34	68.16
7	6.00	22.50	75.30
8	6.00	10.00	90.34
9	8.83	13.66	99.43
10	3.17	13.66	66.71
11	2.00	22.50	73.42
12	10.00	22.50	99.61

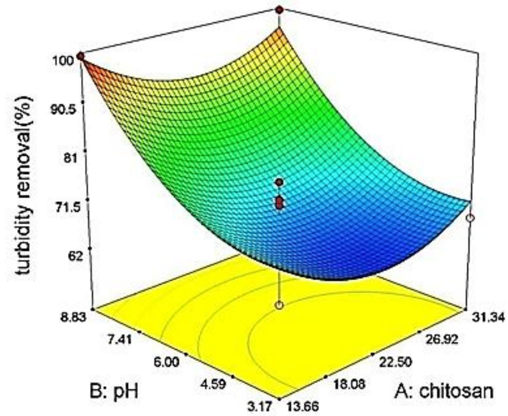


Fig. 3. Evaluation of the impacts of chitosan dose and pH on the percentage turbidity removal.

Table 4. Optimization results in the experiment on chitosan as a coagulant.

Number	Chitosan dose, mg/L	pH	Turbidity removal, %	Desirability
1	13.66	8.83	99.12	0.987
2	13.66	8.78	98.65	0.974
3	31.34	8.83	96.16	0.906

The optimal pH was found to be the one closest to the initial pH of water. Due to its lower dose of the coagulant substance, the first response was deemed the most optimal. In addition, the last column of the above table shows that not all responses are equally desirable. The first response is therefore considered to be the most desirable and should therefore be given priority.

3.3. Coagulation results by PAC

In Table 5, the design independent parameters and levels are shown, while in Table 6, the design matrix and experimental results are presented. Here is the equation of the estimated model based on the experimental results:

$$R\ (\%)= 98.72-0.92A+2.73B-0.062AB-0.59A^2-2.1B^2 \qquad (2)$$

where A and B are the PAC dose and pH value, respectively, based on Fig. 4, the values of pH and PAC significantly affect the amount of turbidity removal. If PAC is raised up to 13 mg/L, turbidity is removed at a higher percentage; however, if PAC is raised higher, turbidity removal is reduced. The results of the optimization process are shown in Table 7.

3.4. Coagulation results by combined PAC and chitosan

This section examines the effects of PAC combined with chitosan. Turbidity removal was the response variable. A central composite design was used with the response surface method (RSM). Tables 8 and 9 show coded factors and matrix design for the simultaneous use of PAC and Chitosan to remove turbidity.

Table 5. Coded levels and factors for CCD study**.**

Level	PAC dose (X1)	pH (X2)
-*α*	3.00	2.00
-1	5.93	3.17
0	13.00	6.00
+1	20.07	8.83
+*α*	23.00	10.00

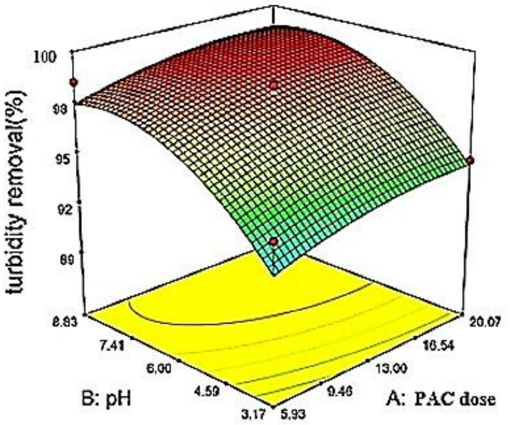


Fig. 4. The evaluation of the impacts of PAC and pH doses on the percentage of turbidity removal.

Table 6. Matrix design for the effective factors for turbidity removal using PAC.

Run no.	Parameters		Turbidity removal, %
	pH	PAC dose, mg/L	
1	6.00	13.00	99.10
2	10.00	13.00	98.10
3	6.00	3.00	94.39
4	6.00	13.00	99.03
5	8.83	5.93	99.25
6	6.00	13.00	98.54
7	2.00	13.00	89.53
8	3.17	20.07	94.63
9	8.83	20.07	99.38
10	6.00	13.00	98.49
11	6.00	23.00	99.25
12	3.17	5.93	94.25

Table 7. Optimization results in the experiment on PAC coagulant.

Number	PAC dose, mg/L	pH	Turbidity removal, %	Desirability
1	12.10	8.64	99.37	0.927
2	12.30	8.60	97.78	0.912
3	12.25	8.68	95.27	0.887

Table 8. Coded levels and factors for CCD study.

Level	PAC dose (X1)	Chitosan dose (X2)	pH (X3)
-*α*	3.00	5.00	5.00
-1	5.93	9.05	6.22
0	13.00	15.00	6.00
+1	20.07	20.95	9.78
+*α*	23.00	25.00	11.00

ANOVA results are provided in Table 10 to determine the efficiency of the model. As the p-value was less than 0.05, the model was found to be efficient. It is also worth noting that chitosan and PAC have probability levels above 0.05, but pH has a lower probability level. pH has a greater impact on turbidity removal than PAC or chitosan doses. As a result, the developed model is formulated as follows:

$$R\ (\%)= 99.13+0.22A-0.1B+2.63C+0.33AB-0.16AC+0.037BC-0.022A^2-0.12B^2-1.75C^2 \qquad (3)$$

A represents PAC concentration, B represents chitosan concentration, and C represents pH concentration. Fig. 5 illustrates the simultaneous effects of PAC and chitosan on turbidity removal. Fig. 5 reveals that an increase in PAC and Chitosan concentrations does not significantly change turbidity removal by more than 5.1 %. Fig. 6 represents the simultaneous effects of PAC and pH on turbidity removal.

Table 9. Matrix design for the effective factors for turbidity removal using PAC and chitosan combination.

Run No.	pH	PAC dose, mg/L	Chitosan dose, mg/L	Turbidity removal, %
1	8.00	3.00	15.00	98.93
2	9.78	7.05	20.95	99.56
3	6.22	7.05	20.95	93.94
4	5.00	13.00	15.00	88.93
5	8.00	13.00	15.00	98.89
6	9.78	7.05	9.05	99.10
7	8.00	23.00	15.00	99.38
8	6.28	7.05	9.05	95.05
9	8.00	13.00	25.00	98.06
10	9.78	18.95	20.95	99.73
11	6.22	18.95	9.05	94.54
12	8.00	13.00	15.00	99.85
13	6.22	18.95	20.95	96.19
14	9.78	18.95	9.05	99.36
15	8.00	13.00	5.00	99.69
16	8.00	13.00	15.00	98.79
17	8.00	13.00	15.00	98.98
18	11.00	13.00	15.00	99.61

Table 10. ANOVA results for turbidity removal.

Source	Sum of squares	P.Value	Remarks
S.S. regression	137.49	0.0001	Significant
A-PAC	0.64	0.3867	
B-Chitosan	0.14	0.6841	
C-pH	94.81	< 0.0001	
AB	0.90	0.3096	
AC	0.21	0.6102	
BC	0.011	0.9078	
A^2	0.0059	0.9319	
B^2	0.18	0.6376	
C^2	38.73	< 0.0001	
Residual	6.09		
Lack of fit	5.37	0.1223	Not significant
S.S. Error	0.71		

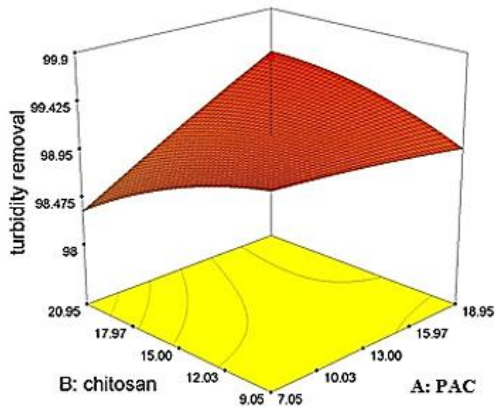


Fig. 5. PAC and chitosan concentrations versus turbidity removal.

In Fig. 6, turbidity removal does not differ as to the PAC concentration changes at a fixed pH. A rise in pH also increases the removal of turbidity at a fixed PAC concentration. As shown in Fig. 7, at a constant pH, chitosan does not affect turbidity removal. An increase in pH increases chitosan's ability to remove turbidity.

3.5. Validation test

In the previous section, the models for each of the coagulants were developed. To test the validity of the estimated models, a response variable was extracted from each independent variable. Experiments were then conducted to determine the response variables for the independent variables (table 12). Based on PAC alone, the constructed model predicted the percentage of turbidity removal with an error of 7.40%. A 0.55 % error value was obtained when only chitosan was used. Furthermore, the combined application of the two substances resulted in a 0.37 % error value, indicating that the constructed model is convenient.

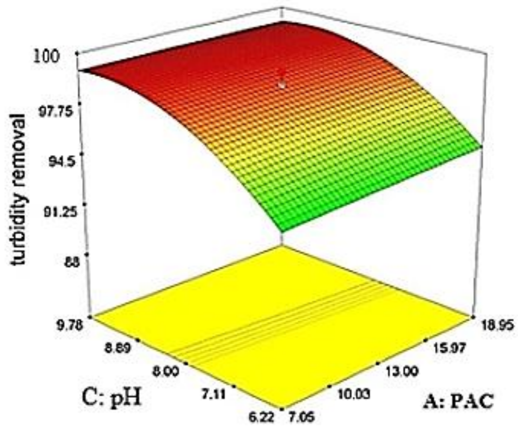


Fig. 6. PAC concentration and pH versus turbidity removal.

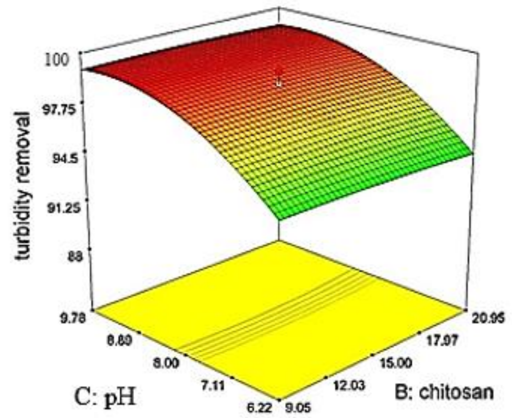


Fig. 7. Chitosan concentration and pH versus turbidity removal.

Table 11 summarizes the optimum results for different types of coagulation. A PAC concentration of 12.11 mg/L removes 99.39 % of turbidity. Furthermore, a chitosan concentration of 13.66 mg/L removes 99.11% of turbidity. By combining PAC (7.6 mg/L) and chitosan (9.28 mg/L), 99.85% of the turbidity was removed. Therefore, the use of PAC and chitosan together reduced the amount of material and enhanced the removal of turbidity (Fig. 8).

Table 11. Optimum results for different coagulation tests.

Test	PAC, mg/L	Chitosan, mg/L	pH	Turbidity removal, %
PAC	12.10	0	8.64	99.37
Chitosan	0	13.66	8.83	99.12
PAC-Chitosan	7.6	9.28	8.52	99.84

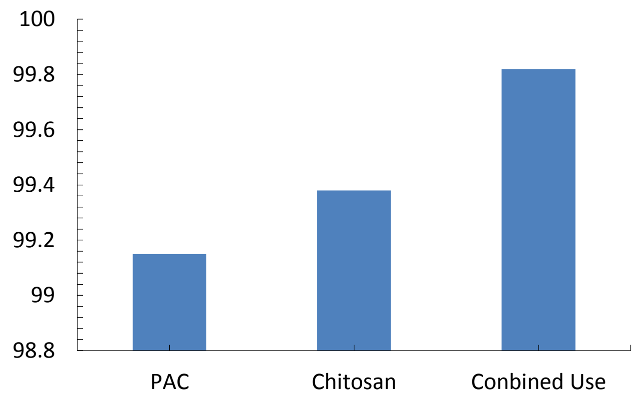


Fig. 8. Comparison of turbidity removal levels in optimal conditions.

Table 12. Validation tests for different coagulants.

Operating condition	Experiment, %	Model, %
PAC		
pH= 6.2, Dose = 11.5	97.26	97.15
pH= 7.8, Dose = 12.8	99.35	99.54
pH= 8.6, Dose = 14.5	98.72	98.65
Chitosan		
pH= 6.4, Dose = 10.5	96.35	96.42
pH= 8.1, Dose = 13.3	98.53	98.75
pH= 9.4, Dose = 15.2	97.20	97.12
Combined use		
pH= 6.5, Dose = 11.3	98.65	98.48
pH= 7.8, Dose = 14.5	99.82	99.76
pH= 9.1, Dose = 16.8	99.26	99.35

4. Conclusions

The results are summarized as follows:

- The combination of PAC and chitosan reduced PAC by 4.51 mg/L. The use of PAC and Chitosan together increased turbidity removal from 99.39 to 99.85 (compared to the use of PAC and Chitosan alone).
- To remove turbidity, pH was more effective than PAC and chitosan, especially when combined with PAC and chitosan. As a result, pH should be adjusted to minimize PAC and chitosan concentrations and maximize efficiency. In water treatment plants, pH adjustment is therefore essential.
- Since PAC is used in the water treatment plant, it is difficult and costly to use a 100% substitute. In combination with PAC, chitosan would reduce PAC usage and improve turbidity removal efficiency. Water treatment plants can make use of natural coagulants because of these advantages. However, the approach must be economically feasible.
- A combination of PAC and chitosan is expected to improve turbidity removal efficiency compared to the use of PAC and chitosan separately. Therefore, this combination could perform better under changing conditions.

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