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Dose–Turbidity Response of Poly Aluminium Chloride in Raw-Water Treatment: Jar Tests and Conditional Feed-Rate Estimation

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ABSTRACT

Poly aluminium chloride (PAC) is used to destabilize suspended and colloidal particles during raw-water clarification. This study evaluates the relationship between PAC dose and residual turbidity for five raw-water samples and estimates a corresponding chemical feed rate for a reported raw-water flow of 200 L/s. Jar tests were conducted using 1,000 mL samples, six PAC doses (30, 32.5, 35, 37.5, 40, and 42.5 mg/L), rapid mixing at 140 rpm for 5 min, slow mixing at 50 rpm for 10 min, and settling for 20 min. Initial turbidity ranged from 25.2 to 51.7 NTU, while final turbidity across all tested conditions ranged from 0.567 to 3.73 NTU. The lowest observed final turbidity for each raw-water sample occurred at 37.5 mg/L for initial turbidities of 25.2, 31.8, and 51.7 NTU, and at 42.5 mg/L for initial turbidities of 27.3 and 30.6 NTU. Thus, the dataset does not support a universal turbidity-minimizing optimum of 30 mg/L. However, 30 mg/L was the lowest tested dose and produced final turbidity values of 1.16–3.73 NTU across the five samples. A feed-rate estimate of approximately 56.07 mL/s at 30 mg/L is obtained only if the reported 10.7% PAC concentration is interpreted as 107 mg/mL (w/v); this concentration basis must be confirmed before operational use. The results provide a site-specific dose-response assessment, but replication, water-chemistry measurements, and field validation are required before the dose can be generalized or described as economically optimal.

Keywords:
poly aluminium chloride; jar test; raw-water clarification; turbidity removal; coagulant dosing; chemical feed rate.

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INTRODUCTION

Raw-Water Turbidity and the Importance of Coagulation

Surface water is an important source of raw water for industrial water supply and public water treatment systems. However, its quality can vary with rainfall, catchment conditions, erosion, and the transport of suspended particles. Turbidity is a key physical indicator of water quality because it reflects the presence of suspended and colloidal particles, including clay, silt, organic matter, and other fine materials (Aulenbach et al., 2022, p. 57; Santana et al., 2021, p. 5). These particles can affect water clarification and complicate subsequent treatment processes. The World Health Organization (WHO, 2017) emphasizes that turbidity should be considered throughout the water supply chain because it provides information about source-water conditions and can influence the effectiveness of treatment barriers.

Coagulation is widely applied to destabilize colloidal particles that do not readily settle under gravity. The process involves adding a chemical coagulant that promotes particle aggregation through mechanisms such as charge neutralization and the formation of metal hydroxide precipitates (Shim et al., 2014, p. 133; Sukmana et al., 2021, p. 57). These mechanisms facilitate the formation of larger aggregates, commonly referred to as flocs, which can subsequently be removed through sedimentation and filtration (Turner et al., 2019, p. 2). However, coagulation performance depends on the chemical properties of the coagulant and the characteristics of the water being treated. The relative contributions of charge neutralization and sweep flocculation are influenced by coagulant dosage, pH, and the hydrolysis behavior of the added metal species (Duan & Gregory, 2003).

The importance of coagulation is particularly evident in treatment plants that process surface water with variable turbidity. An operating condition that performs adequately under one set of raw-water conditions may not provide equivalent performance when the source-water characteristics change (Cui et al., 2020, p. 20232; Wang et al., 2023). Consequently, determining a suitable coagulant dose is an important operational task. The dose must provide

sufficient particle destabilization and removal while avoiding unnecessary chemical consumption. A site-specific assessment is therefore required to connect laboratory coagulation performance with the operating conditions of a water treatment plant.

Poly Aluminium Chloride and the Determination of Coagulant Dosage

Poly aluminium chloride (PAC), also commonly referred to in the scientific literature as polyaluminum chloride (PACl), is a prehydrolyzed aluminium-based coagulant used in water treatment. Its performance is associated with the distribution of aluminium species, their hydrolysis characteristics, and their interactions with suspended particles and dissolved organic matter. Depending on water chemistry and coagulation conditions, PAC can promote particle destabilization and the formation of aggregates that are more readily separated from water (Duan & Gregory, 2003; Yan, Wang, Ni, et al., 2008; Yan, Wang, Yu, et al., 2008).

Nevertheless, PAC performance cannot be assessed independently of raw-water chemistry. (Pernitsky & Edzwald, 2006) showed that coagulant selection and application depend on several water-quality characteristics, including natural organic matter, alkalinity, and coagulation pH. These factors affect the suitability of different aluminium-based coagulants and the conditions under which they perform effectively. Similarly, (Yan et al., 2008) demonstrated that pH, alkalinity, coagulant basicity, and aluminium speciation influence coagulation performance. These findings indicate that a PAC dosage identified under one set of conditions should not automatically be considered optimal for another water source.

The jar test is a practical laboratory procedure for evaluating coagulation performance under controlled mixing and settling conditions. By applying different coagulant doses to representative raw-water samples, the procedure enables the comparison of residual turbidity after treatment (Konkobo et al., 2023, p. 2; Postolachi et al., 2015, p. 26). However, the lowest residual turbidity observed in a limited dose range is not necessarily equivalent to the overall optimum operating condition. A comprehensive optimization should also consider other relevant responses, such as pH, residual aluminium, sludge production, filtration performance, and chemical consumption, depending on the treatment objective(Zainal-Abideen et al., 2012).

Previous investigations illustrate the importance of evaluating both dosage and water chemistry. Mazloomi et al. (2018) examined PAC application under different dosage and pH conditions and reported that turbidity removal was influenced by the treatment conditions, particularly pH. Their study demonstrates why dosage-response relationships must be interpreted in the context of the water being treated. In another investigation, Zainal-Abideen et al. (2012) compared conventional jar test optimization with a statistical experimental design approach. Their findings showed that the estimated coagulation conditions differed between the two approaches, demonstrating the potential value of systematic experimental design in selecting operating conditions. More recently, Holloway et al. (2022) evaluated several aluminium-based coagulants and applied central composite design and response surface methodology to optimize the dosage and pH of a selected PACl product. Their results further illustrate that coagulant performance and operating conditions require empirical evaluation rather than assumptions based solely on the general properties of the chemical.

Although these studies provide a strong basis for understanding PAC coagulation and dosage optimization, their findings also indicate that the most suitable operating conditions depend on the specific coagulant, raw-water characteristics, and treatment objectives. Therefore, results obtained from different treatment plants cannot be transferred directly to another facility without considering differences in water quality, operating conditions, and the concentration of the commercial coagulant solution.

Operational Problem and Research Gap at PT X

At PT X, raw water is treated through a sequence of processes that includes preliminary settling, coagulation and flocculation, sedimentation, filtration, and disinfection. PAC is injected into the incoming raw water to support the removal of suspended and colloidal impurities. Because the plant processes surface water, changes in raw-water turbidity create an operational need to evaluate the suitability of the applied coagulant dosage under different source-water conditions.

The original investigation reported five raw-water turbidity conditions of 25.2, 27.3, 30.6, 31.8, and 51.7 nephelometric turbidity units (NTU). The jar tests evaluated six PAC dosages, namely 30, 32.5, 35, 37.5, 40, and 42.5 ppm. The reported laboratory procedure used a rapid-mixing stage at 140 rpm for 5 min, followed by slow mixing at 50 rpm for 10 min and settling for 20 min. The reported raw-water flow rate at the treatment plant was 200 L/s. These operating and experimental conditions provide a basis for examining the relationship between PAC dosage and residual turbidity across the investigated raw-water conditions.

The practical issue is not simply whether PAC can reduce turbidity. Rather, the relevant question is how the observed laboratory response can inform the selection of a suitable dose and its translation into a chemical injection requirement at the plant scale. A dose expressed in ppm or mg/L describes the amount of coagulant applied relative to the volume of water, whereas the injection flow rate expresses the volume of coagulant solution delivered per unit time. Converting between these quantities requires a consistent mass balance and reliable information about the concentration and, where relevant, the density of the PAC solution. An appropriate laboratory dose therefore cannot be translated into a defensible plant injection rate without establishing the concentration basis used in the calculation.

The existing literature provides evidence on PAC coagulation mechanisms, the influence of water chemistry, and methods for determining suitable operating conditions (Holloway et al., 2022; Pernitsky & Edzwald, 2006; Zainal-Abideen et al., 2012). However, the operational question addressed in the present study is specific to the reported conditions at PT X: how do the tested PAC dosages perform across five raw-water turbidity conditions, and how can the selected dosage be related to the plant's reported raw-water flow rate? The present study does not assume that this site-specific assessment establishes a universal optimum for PAC application. Instead, it evaluates the available dose-response data and examines their implications for operational dosing calculations.

The study also has limitations that define the scope of its contribution. The reported jar test uses a fixed mixing and settling procedure and a finite range of PAC dosages. The available experimental record does not establish the effects of varying pH, alkalinity, or PAC basicity, and it does not document replicate measurements for every experimental condition. These factors limit the extent to which the results can be generalized to other raw-water sources or operating periods. Furthermore, a dose that produces the lowest measured residual turbidity within the tested range should be distinguished from an economically optimal dose, which requires an explicit assessment of chemical consumption and other relevant operating costs.

Research Objectives, Questions, and Contributions

The objective of this study is to evaluate the response of raw water from PT X to different PAC dosages using jar tests and to examine the implications of the observed response for chemical dosing at the reported plant flow rate. The investigation focuses on the relationship between initial turbidity, PAC dosage, residual turbidity, and the calculation of the corresponding injection requirement. The study addresses the following research questions: 1) How does residual turbidity vary with PAC dosage under the five investigated raw-water turbidity conditions? 2) Which of the tested PAC dosages produces the lowest observed residual turbidity for each raw-water condition? 3) How can the laboratory dosage be translated into a plant-scale PAC injection flow rate at a reported raw-water flow of 200 L/s, given a verified PAC solution concentration and a consistent calculation basis?

The contribution of this study is threefold. First, it provides a site-specific comparison of PAC dose-response behavior across a range of initial turbidity conditions using the reported jar test data. Second, it distinguishes the best-performing dosage within the tested range from a fully optimized operating condition, thereby establishing an appropriate basis for interpreting the laboratory results. Third, it connects laboratory dosage assessment with the operational calculation of PAC injection requirements, subject to verification of the concentration and physical properties of the coagulant solution. By linking laboratory observations to plant-scale dosing calculations, the study aims to provide practical evidence for evaluating PAC application at PT X. Its findings are intended to support site-specific operational assessment rather than to establish a universally applicable dosage. Further validation using replicated experiments, additional water-quality parameters, and operating data collected over time would be necessary to determine the robustness of the selected conditions and to establish whether they remain suitable under changing raw-water quality.

MATERIALS AND METHODS

Materials, Equipment, and Research Conditions

The study used raw river water and liquid poly aluminium chloride (PAC) as the principal experimental materials. The raw water was obtained from the source-water supply associated with the water treatment plant (WTP) at PT X, where PAC is applied before flocculation, sedimentation, and filtration. Five raw-water conditions were investigated, with initial turbidity values of 25.2, 27.3, 30.6, 31.8, and 51.7 nephelometric turbidity units (NTU). The reported raw-water flow rate at the treatment plant was 200 L/s. The laboratory equipment comprised 1,000 mL beakers for the jar tests, a measuring pipette, a volumetric flask, a syringe for coagulant addition, a 1,000 mL graduated cylinder, a Baumé hydrometer, cuvettes, and a TL2350 turbidity meter. The Baumé hydrometer was used to determine the specific-gravity-related reading of the liquid PAC, which was subsequently compared with a PAC concentration table available at PT X. The turbidity meter was used to measure the initial and final turbidity of the water samples.

A 1% PAC stock solution was reported to have been prepared for the laboratory experiments. The original laboratory record did not explicitly define whether this concentration was expressed on a mass-per-volume or mass-per-mass basis. However, the recorded addition volumes of 3.00–4.25 mL per 1,000 mL sample are consistent with a nominal 1% (w/v) stock solution when the tested doses are expressed as 30–42.5 mg/L. This interpretation is used to explain the recorded dosing procedure and should be confirmed against the original laboratory preparation records. The PAC concentration used for the plant-scale feed-rate calculation was reported as 10.7%. The original record did not establish whether this value represented a mass fraction, a mass-per-volume concentration, or another concentration basis. Consequently, the reported concentration was not treated as an independently verified active-PAC concentration. The corresponding feed-rate calculation is presented conditionally in Section 2.4. The source study did not report the water temperature, pH, alkalinity, PAC product basicity, aluminium oxide content, instrument measurement uncertainty, or detailed instrument calibration records. These parameters were therefore not included as measured variables in the present analysis.

Experimental Design and Jar-Test Procedure

The study employed a laboratory jar-test procedure to examine the relationship between PAC dosage and residual turbidity under five initial raw-water turbidity conditions. Six PAC dosage levels were evaluated for each condition: 30, 32.5, 35, 37.5, 40, and 42.5 mg/L. The experimental design therefore comprised 30 dose-condition combinations, with each reported combination represented by one recorded final-turbidity measurement. Replicate measurements were not reported in the source data. For each initial turbidity condition, six 1,000 mL beakers were filled with raw-water samples. Different volumes of the 1% PAC stock solution were then added to obtain the six nominal dosage levels. Based on the recorded addition volumes, the stock-solution volumes were 3.00, 3.25, 3.50, 3.75, 4.00, and 4.25 mL per 1,000 mL sample, corresponding to nominal doses of 30, 32.5, 35, 37.5, 40, and 42.5 mg/L, respectively, under the 1% (w/v) interpretation. After PAC addition, the samples were subjected to the mixing and settling sequence reported in the original study:

Rapid mixing: 140 rpm for 5 min to promote initial contact and dispersion of the coagulant.

Slow mixing: 50 rpm for 10 min to facilitate particle aggregation and floc formation.

Settling: 20 min without mechanical mixing to allow the formed flocs to settle.

Following the settling period, the supernatant was sampled for final-turbidity measurement. The same reported mixing

and settling conditions were applied across the tested PAC dosages to maintain procedural consistency.

The independent experimental factors were the nominal PAC dose and the initial raw-water turbidity condition. Final turbidity was the principal response variable. Because the original study did not report a coagulant-free control, repeated trials, or randomized treatment order, the design supports descriptive comparisons among the recorded dose-condition combinations but does not establish statistical significance or experimental repeatability.

Process Parameters and Measurement Procedures

The main process parameters were initial turbidity, PAC dose, final turbidity, and raw-water flow rate. Initial turbidity represented the condition of each raw-water sample before coagulation treatment, whereas final turbidity represented the measured turbidity after PAC addition, mixing, and settling. Initial turbidity values were taken from the recorded raw-water operating data. Final turbidity was measured using the TL2350 turbidity meter. Before measurement, the treated-water sample was transferred into a cuvette up to the designated filling mark. The outside of the cuvette was cleaned with tissue, and the cuvette was positioned in the instrument according to the measurement procedure described in the original laboratory record. The instrument reading was then recorded in NTU.

The nominal PAC dose was expressed in mg/L, equivalent to ppm for dilute aqueous dosing calculations under the convention used in the original study. The dosage levels were compared using the measured final turbidity for each initial turbidity condition. The raw-water flow rate of 200 L/s was taken from the reported plant operating data and was used only for the conditional calculation of the PAC injection flow rate. The percentage reduction in turbidity was calculated using Equation (1):

$$R = \left(\frac{T_0 - T_f}{T_0}\right) \times 100 \quad (1)$$

where (R) is the turbidity removal efficiency (%), T_0 is the initial turbidity (NTU), and T_f is the final turbidity after the jar test (NTU).

This equation was applied to each recorded dose-condition combination. The resulting percentage represents the reduction relative to the initial turbidity of the corresponding raw-water sample. It does not represent the removal of all contaminants or establish the microbiological safety of the treated water.

The original record did not provide instrument accuracy, calibration results, replicate measurements, or uncertainty estimates. Accordingly, the reported turbidity values were treated as single observations, and no uncertainty interval was assigned to the calculated removal efficiencies.

Dose-Response Analysis and PAC Feed-Rate Calculation

Identification of the best-performing tested dose

The dose-response analysis compared the final turbidity obtained at the six tested PAC dosages for each of the five initial turbidity conditions. For each condition, the best-performing tested dose was defined operationally as the dose associated with the lowest recorded final turbidity among the six tested levels. This definition refers only to the minimum observed turbidity within the tested dose range. It does not establish a universal optimum, an economically optimal dose, or a statistically validated operating condition. The lowest tested dose, 30 mg/L, was also retained as a reference point for evaluating the relationship between reduced chemical dosage and residual turbidity. The comparison was based on the observed final-turbidity values and the removal efficiencies calculated using Equation (1). No regression model, response surface model, or inferential statistical test was fitted because the source dataset did not include reported replicate measurements or sufficient experimental information to estimate experimental error reliably.

Preparation of the laboratory PAC stock solution

The original procedure reported preparation of a 1% PAC stock solution using a volumetric flask and a dilution calculation based on the initial PAC concentration. The general dilution relationship is expressed as Equation (2):

$$C_1\, V_1 = C_2 V_2 \quad (2)$$

where (C_1) is the initial concentration, (V_1) is the volume of the initial PAC solution required, (C_2) is the target stock-solution concentration, and (V_2) is the final stock-solution volume.

For a nominal 1% (w/v) stock solution, the concentration is equivalent to 10 mg/mL on the same mass basis used to define the percentage. The volume required to obtain a target nominal dose in a laboratory sample was calculated using Equation (3):

$$V_s = \frac{D \times V_w}{C_s} \quad (3)$$

where (V_s) is the stock-solution volume added (mL), (D) is the target dose (mg/L), (V_w) is the sample volume (L), and (C_s) is the stock-solution concentration (mg/mL).

For a 1,000 mL sample, $(V_w = 1)$ L. If $(C_s = 10)$ mg/mL, the calculated stock-solution volumes are 3.00, 3.25, 3.50, 3.75, 4.00, and 4.25 mL for the respective target doses of 30, 32.5, 35, 37.5, 40, and 42.5 mg/L.

These calculations reproduce the nominal dosing basis indicated by the recorded jar-test volumes. Because the percentage basis and the definition of the PAC mass used in the original stock preparation were not explicitly documented, the concentrations should be understood as nominal values pending confirmation from the laboratory records.

Conditional calculation of the plant-scale PAC injection flow rate

The PAC injection flow rate was estimated from the nominal coagulant dose and the reported raw-water flow rate using a mass-balance relationship:

$$Q_{PAC} = \frac{D \times Q_w}{C_{PAC}} \quad (4)$$

where $(Q_{\{\backslash mathrm\{PAC\}\}})$is the volumetric PAC solution feed rate (mL/s), (D) is the nominal PAC dose (mg/L), $(Q_w)$is the raw-water flow rate (L/s), and $(C_{\{\backslash mathrm\{PAC\}\}})$ is the concentration of the dosing solution on the same mass basis as the applied dose (mg/mL).

Equation (4) follows from the relationship between the required coagulant mass flow and the concentration of the dosing solution. The required coagulant mass flow is (D Q_w), expressed in mg/s. Dividing this value by $(C_{\{\backslash mathrm\{PAC\}\}}$ expressed in mg/mL, gives the corresponding volumetric feed rate in mL/s. For the reported raw-water flow rate of 200 L/s and nominal PAC dose of 30 mg/L, the required nominal coagulant mass flow is:

$$\dot{m}_{PAC} = 30 \times 200 = 6000 \frac{mg}{s} \quad (5)$$

The original reported injection rate of approximately 56.07 mL/s can be reproduced if the reported PAC concentration of 10.7% is interpreted as 10.7% (w/v), equivalent to 107

mg/mL on the same mass basis. Under this explicit assumption:

$$Q_{PAC} = \frac{30 \times 200}{107} \approx 56{,}07 \frac{mL}{s} \quad (6)$$

This value is a conditional calculation rather than a verified plant operating rate. If 10.7% represents a mass fraction (w/w), the density of the commercial PAC solution and the precise concentration definition are required to convert it into mg/mL. If the percentage refers to aluminium oxide content or another product specification, the dose basis must also be reconciled before Equation (4) can be applied.

Under the same assumed concentration of 107 mg/mL and a constant raw-water flow rate of 200 L/s, the calculated volumetric feed rate increases linearly with the nominal dose. Equation (4) was therefore used to estimate the corresponding feed rates for the other tested doses. These estimates are presented as conditional calculations for comparison, not as confirmed operating settings for the plant.

Validation and Performance Evaluation

Performance evaluation was based on the measured final turbidity and calculated turbidity removal efficiency for each recorded jar-test condition. The primary comparison was the final turbidity across the six PAC doses within each initial turbidity condition. The dose associated with the lowest recorded final turbidity was identified as the best-performing tested dose. The response at 30 mg/L was additionally evaluated because it was the lowest dose included in the experimental range.

The reported results were assessed for internal consistency by checking whether the selected dose corresponded to the lowest recorded final turbidity and whether the reported PAC injection flow rate was consistent with the stated dose, raw-water flow, and assumed solution concentration. Under a constant solution concentration and raw-water flow rate, different target doses should produce different calculated injection flow rates. Accordingly, the same injection rate cannot represent all six target doses under the assumptions of Equation (4). The available data permit a descriptive evaluation of the recorded dose-response patterns and a conditional mass-balance calculation. However, the source study did not report replicate jar tests, a coagulant-free control, independent validation experiments, or field measurements confirming the calculated injection rate. Consequently, experimental repeatability, statistical significance, and agreement between the calculated and actual plant feed rates could not be established.

The evaluation was also limited to turbidity. Other indicators relevant to operational optimization, including treated-water pH, residual aluminium, sludge production, filtration performance, and chemical consumption costs, were not reported. The analysis therefore does not establish an economically optimal dose or confirm compliance with all applicable water-quality requirements.

Data Analysis and Reproducibility

The dataset was organized by initial turbidity condition and nominal PAC dose. The five initial turbidity conditions were cross-referenced with the six tested doses to produce 30 dose-condition records. The reported final-turbidity values were retained as recorded in the source document. Percentage turbidity removal was calculated using Equation (1), and the best-performing tested dose for each initial turbidity condition was identified by selecting the minimum recorded final-turbidity value. The conditional PAC injection flow rates were calculated using Equation (4), with a raw-water flow rate of 200 L/s and an explicitly stated assumption of 107 mg/mL for the dosing-solution concentration. The calculation was repeated for each nominal dose to examine the expected proportional relationship between dose and feed rate under constant flow and solution concentration. The analysis was descriptive. No inferential statistical tests were performed because replicate measurements and estimates of experimental variability were not available. No missing observations were imputed, and no outlier-removal procedure was applied. All 30 reported final-turbidity measurements were retained in the analysis.

The original study did not report the software used for data processing, instrument calibration records, the exact dates of sample collection, or the order in which the jar tests were conducted. These details are therefore not specified in the present Methods section. Reproduction of the laboratory procedure is possible from the reported sample volume, dose levels, mixing speeds, mixing durations, settling time, and turbidity measurement procedure. Full replication of the study would additionally require confirmation of the PAC stock-solution preparation, the commercial product concentration basis, and the instrument calibration and measurement procedures.

The calculations and interpretations are restricted to the data and operating conditions reported in the source study. The resulting dose-response comparisons and feed-rate estimates should be interpreted as a site-specific assessment. Replicated experiments, additional water-quality measurements, verified PAC product specifications, and field validation are required before the results can be used to establish a robust operational dosing recommendation.

RESULTS

Raw-Water Conditions and Experimental Dataset

The dataset comprised five initial raw-water turbidity conditions: 25.2, 27.3, 30.6, 31.8, and 51.7 NTU. The reported plant raw-water flow rate was 200 L/s. For each initial turbidity condition, six PAC doses (30, 32.5, 35, 37.5, 40, and 42.5 mg/L) were evaluated, yielding 30 dose-condition observations. The source record reports one final-turbidity value for each combination; replicate measurements were not documented.

Table 1. Raw-water conditions and experimental design

Condition	Initial turbidity (NTU)	Raw-water flow (L/s)	PAC doses tested (mg/L)
1	25.2	200	30; 32.5; 35; 37.5; 40; 42.5
2	27.3	200	30; 32.5; 35; 37.5; 40; 42.5
3	30.6	200	30; 32.5; 35; 37.5; 40; 42.5
4	31.8	200	30; 32.5; 35; 37.5; 40; 42.5
5	51.7	200	30; 32.5; 35; 37.5; 40; 42.5

Effect of PAC Dosage on Final Turbidity

Final turbidity varied with PAC dose under all five initial turbidity conditions. The response was not consistently monotonic: increasing the dose did not always produce a lower final turbidity. Across the 30 observations, final turbidity ranged from 0.567 to 3.730 NTU. The minimum recorded value, 0.567 NTU, occurred at an initial turbidity of 51.7 NTU and a PAC dose of 37.5 mg/L. The maximum recorded value, 3.730 NTU, occurred at an initial turbidity of 27.3 NTU and a dose of 30 mg/L.

For an initial turbidity of 25.2 NTU, final turbidity decreased from 1.740 NTU at 30 mg/L to 0.728 NTU at 37.5 mg/L, then increased to 1.080 and 1.170 NTU at 40 and 42.5 mg/L, respectively. At 27.3 NTU, the final turbidity fell from 3.730 NTU at 30 mg/L to 0.827 NTU at 37.5 mg/L and reached 0.779 NTU at 42.5 mg/L. At 30.6 NTU, the response was irregular: final turbidity increased to 1.780 NTU at 37.5 mg/L after declining at lower doses, then decreased to 1.000 NTU at 42.5 mg/L. At 31.8 NTU, the minimum was 0.820 NTU at 37.5 mg/L, whereas the 40 mg/L observation increased to 1.460 NTU. At 51.7 NTU, final turbidity decreased to 0.567 NTU at 37.5 mg/L but increased to 1.210 NTU at 40 mg/L before declining to 0.653 NTU at 42.5 mg/L.

Table 2. Final turbidity and calculated turbidity removal for all jar-test observations

Initial turbidity (NTU)	PAC dose (mg/L)	Final turbidity (NTU)	Turbidity removal (%)
25.2	30	1.74	93.10
25.2	32.5	1.56	93.81
25.2	35	1.46	94.21
25.2	37.5	0.728	97.11
25.2	40	1.08	95.71
25.2	42.5	1.17	95.36
27.3	30	3.73	86.34
27.3	32.5	1.12	95.90
27.3	35	1.11	95.93
27.3	37.5	0.827	96.97
27.3	40	0.952	96.51
27.3	42.5	0.779	97.15
30.6	30	2.71	91.14
30.6	32.5	1.26	95.88
30.6	35	1.09	96.44
30.6	37.5	1.78	94.18
30.6	40	1.07	96.50
30.6	42.5	1.00	96.73
31.8	30	1.16	96.35
31.8	32.5	1.10	96.54
31.8	35	0.915	97.12
31.8	37.5	0.820	97.42
31.8	40	1.46	95.41
31.8	42.5	0.938	97.05
51.7	30	1.19	97.70
51.7	32.5	0.782	98.49
51.7	35	0.756	98.54
51.7	37.5	0.567	98.90
51.7	40	1.21	97.66
51.7	42.5	0.653	98.74

Turbidity Removal Efficiency and Best-Performing Tested Dose

Calculated turbidity removal ranged from 86.34% to 98.90% across the 30 dose-condition observations. The lowest removal efficiency was 86.34% at an initial turbidity of 27.3 NTU and a dose of 30 mg/L. The highest was 98.90% at an initial turbidity of 51.7 NTU and a dose of 37.5 mg/L. The best-performing tested dose, defined as the dose with the lowest recorded final turbidity within the tested range, differed across initial turbidity conditions.

Table 3. Best-performing tested dose for each initial turbidity condition

Initial turbidity (NTU)	Best-performing tested dose (mg/L)	Final turbidity (NTU)	Removal (%)	Lowest observed turbidity among tested doses
25.2	37.5	0.728	97.11	Yes
27.3	42.5	0.779	97.15	Yes
30.6	42.5	1.00	96.73	Yes
31.8	37.5	0.820	97.42	Yes
51.7	37.5	0.567	98.90	Yes

The minimum observed final turbidity occurred at 37.5 mg/L for initial turbidity conditions of 25.2, 31.8, and 51.7 NTU. For initial turbidity values of 27.3 and 30.6 NTU, the lowest measured final turbidity occurred at 42.5 mg/L. These results do not support a single dose as the minimum-turbidity dose for all five conditions. Because the dataset contains no reported replicate measurements and only six dose levels, these values identify the best-performing tested dose rather than a statistically validated or universal optimum.

PAC Injection-Flow Calculations

The plant-scale PAC feed rate was calculated conditionally from the reported raw-water flow rate of 200 L/s and the nominal dose. The original study reported a PAC concentration of 10.7% but did not specify the concentration basis. To reproduce the reported injection rate, the calculation assumes that 10.7% means 10.7% (w/v), equivalent to 107 mg/mL. Under this assumption, the calculated injection rate for a dose of 30 mg/L is 56.07 mL/s. The calculation is conditional and should not be interpreted as a verified plant feed rate until the PAC product specification and concentration basis have been confirmed.

With the assumed concentration held constant, the calculated volumetric feed rate increases in direct proportion to the target dose. Therefore, the injection rate differs for each tested dose, rather than remaining constant at 56.07 mL/s. Table 4 summarizes the resulting conditional estimates.

Table 4. Conditional PAC injection-flow estimates at a raw-water flow of 200 L/s

Nominal PAC dose (mg/L)	Raw-water flow (L/s)	Assumed PAC solution concentration (mg/mL)	Calculated injection flow (mL/s)
30	200	107 (assumed)	56.07
32.5	200	107 (assumed)	60.75
35	200	107 (assumed)	65.42
37.5	200	107 (assumed)	70.09
40	200	107 (assumed)	74.77
42.5	200	107 (assumed)	79.44

The estimated feed rates range from 56.07 mL/s at 30 mg/L to 79.44 mL/s at 42.5 mg/L under the stated assumption. If the reported 10.7% is a mass fraction rather than a mass-per-volume concentration, solution density and the exact dose basis are required to obtain a valid volumetric injection rate. The estimates therefore provide a calculation framework for checking the dosing requirement, not a confirmed operating recommendation.

Dose-Response Figures

Figures 1–5 show the recorded final turbidity as a function of PAC dose for each initial turbidity condition. Each figure presents one initial turbidity condition to make non-monotonic responses and the minimum recorded value visible without combining different raw-water conditions on a single axis.

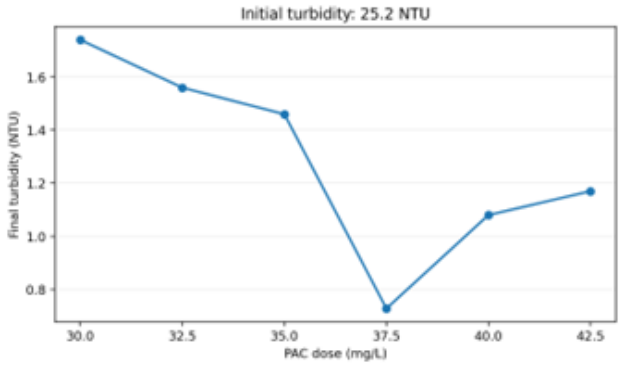


Figure 1. Effect of PAC dosage on final turbidity for raw water with an initial turbidity of 25.2 NTU.

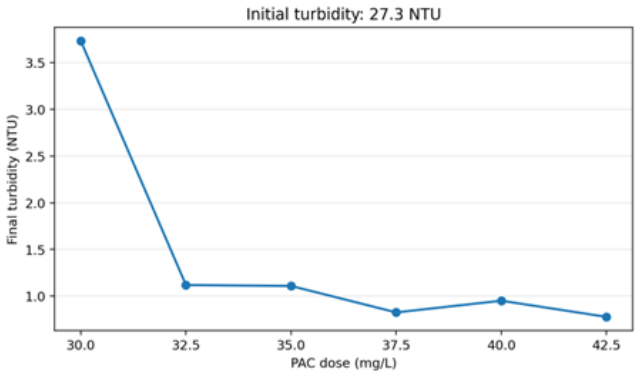


Figure 2. Effect of PAC dosage on final turbidity for raw water with an initial turbidity of 27.3 NTU.

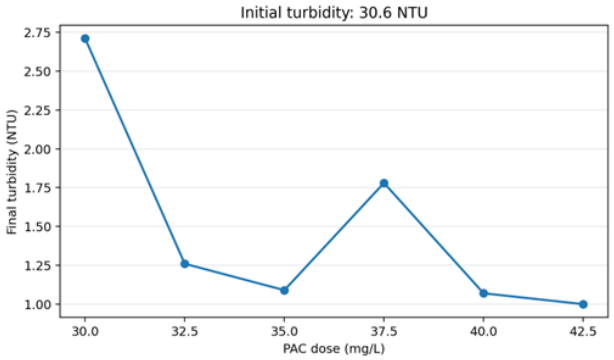


Figure 3. Effect of PAC dosage on final turbidity for raw water with an initial turbidity of 30.6 NTU.

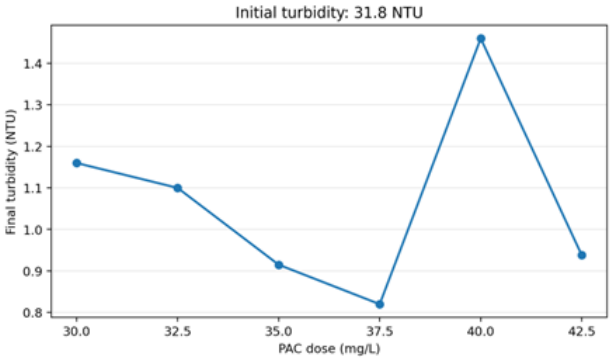


Figure 4. Effect of PAC dosage on final turbidity for raw water with an initial turbidity of 31.8 NTU.

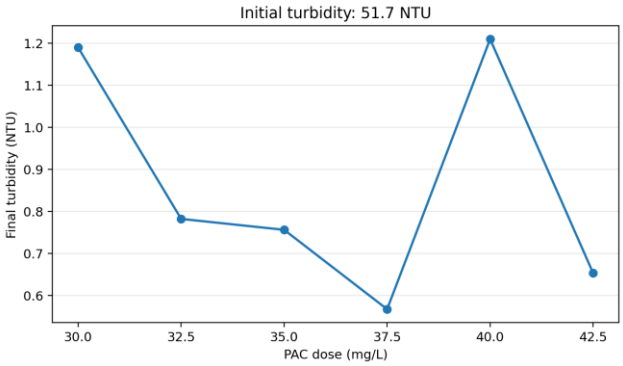


Figure 5. Effect of PAC dosage on final turbidity for raw water with an initial turbidity of 51.7 NTU.

Summary of Main Results

The jar-test dataset shows that PAC reduced turbidity under all five initial raw-water conditions, with calculated removal efficiencies ranging from 86.34% to 98.90%. However, the final-turbidity response was not consistently monotonic as the dose increased. The best-performing tested dose was 37.5 mg/L for initial turbidity values of 25.2, 31.8, and 51.7 NTU, and 42.5 mg/L for initial turbidity values of 27.3 and 30.6 NTU. The plant-scale injection rates can be calculated from the reported water flow and nominal dose, but the numerical estimates remain conditional on verification of the reported 10.7% PAC concentration basis.

DISCUSSION

Interpretation of PAC Dose–Response Behaviour

The results demonstrate that PAC reduced turbidity under all five investigated raw-water conditions. However, the relationship between PAC dosage and residual turbidity was not consistently monotonic. The lowest measured final turbidity occurred at 37.5 mg/L for initial turbidity values of 25.2, 31.8, and 51.7 NTU, whereas 42.5 mg/L produced the lowest measured final turbidity for initial turbidity values of 27.3 and 30.6 NTU. These differences indicate that the dose associated with the lowest observed residual turbidity varied across the investigated water samples.

This variation is important because it shows that a single PAC dose cannot be identified as the best-performing dose for all five conditions based solely on the recorded measurements. The results support a site-specific assessment of coagulation performance rather than the assumption that increasing the coagulant dose will consistently improve clarification. Nevertheless, the differences between the observed responses cannot be attributed exclusively to initial turbidity because other potentially influential water-quality parameters, including pH, alkalinity, and natural organic matter content, were not reported.

The measured turbidity removal efficiencies ranged from 86.34% to 98.90%. The highest removal efficiency occurred at an initial turbidity of 51.7 NTU and a PAC dose of 37.5 mg/L. In contrast, the lowest removal efficiency occurred at an initial turbidity of 27.3 NTU and a dose of 30 mg/L. These observations indicate that the initial turbidity alone does not provide sufficient information to predict the residual turbidity achieved at a particular coagulant dose. The composition and physicochemical characteristics of the raw water may also influence coagulation performance.

The results should therefore be interpreted as evidence of the observed dose–response behaviour within the tested range of 30–42.5 mg/L. They do not establish a universal optimum or demonstrate that the selected doses would remain optimal under different source-water conditions. In particular, the lowest residual turbidity for the 27.3 and 30.6 NTU conditions occurred at the upper boundary of the tested dose range, 42.5 mg/L. Because higher doses were not investigated, the data cannot establish whether these responses would continue to improve, reach a plateau, or deteriorate beyond the tested range.

Coagulation Mechanisms and Comparison with Previous Studies

The observed dose-dependent variation is consistent with the established understanding that aluminium-based coagulants operate through mechanisms influenced by coagulant dosage and water chemistry. Duan & Gregory (2003) explained that coagulation by hydrolysing metal salts involves mechanisms such as charge neutralisation and sweep flocculation. In charge neutralisation, positively charged hydrolysis products interact with negatively charged colloidal particles, reducing electrostatic repulsion and facilitating aggregation (Ghernaout & Boucherit, 2015, p. 26; Gregory & Duan, 2001, p. 2021). In sweep flocculation, particles become incorporated into precipitating metal hydroxide structures (Appiah-Brempong et al., 2021, p. 21; Honda et al., 2014, p. 128). The relative importance of these mechanisms depends on conditions such as pH and coagulant dosage.

These mechanisms provide a scientific basis for interpreting the differences observed in the present study. At an appropriate dose, PAC may destabilise colloidal particles and facilitate the formation of aggregates that settle more readily. However, increasing the dose does not necessarily produce a proportional reduction in residual turbidity. Coagulation performance depends on the relationship between the added coagulant, the available particles, and the chemical conditions of the water. Excessive dosage can, under certain conditions, alter particle surface charge and promote colloidal restabilisation (Baghvand, 2010, p. 444; Saritha et al., 2015, p. 458). Nevertheless, the present study did not measure zeta potential, aluminium speciation, or particle charge. Therefore, charge reversal or restabilisation cannot be established as the cause of the non-monotonic responses observed in the experimental data.

The influence of water chemistry is further supported by Pernitsky & Edzwald (2006), who demonstrated that the selection and application of aluminium-based coagulants depend on raw-water characteristics, including natural organic matter and alkalinity, as well as the pH associated with coagulation. Yan et al. (2008) similarly showed that pH, alkalinity, and aluminium speciation influence the performance of polyaluminium chloride coagulants. Their findings indicate that coagulant dosage should be evaluated in conjunction with relevant water-quality parameters rather than considered as an isolated operating variable. Consistent with this perspective, the present findings suggest that the apparent optimum dose in this study should be regarded as conditional on the specific raw-water chemistry under which the jar tests were performed, rather than as a transferable operating value for the treatment plant. Future work should therefore couple jar-test dose screening with measurements of pH, alkalinity, and aluminium speciation so that the conditions governing the observed responses can be identified directly rather than inferred (Maldhure et al., 2021, p. 2798).

This evidence helps explain why the same nominal dose may produce different residual turbidity values under different raw-water conditions. However, the current dataset does not contain sufficient water-chemistry measurements to determine which mechanism dominated at PT X. The mechanistic interpretation should therefore remain a scientifically supported explanation of possible behaviour rather than a direct experimental finding of this study.

The present findings also align with research demonstrating the value of systematic jar-test evaluation. Zainal-Abideen et al. (2012) compared conventional jar-test optimisation with response surface methodology (RSM) and found that the estimated operating conditions differed between the approaches. Their study illustrates that the method used to identify operating conditions can influence the resulting dose selection. Similarly, Holloway et al. (2022) evaluated aluminium-based coagulants and used central composite design and RSM to investigate the effects of dosage and pH on settled and filtered turbidity. Their work demonstrated the value of evaluating coagulant dosage alongside other influential operating parameters. Within the present study's operating range, this approach indicates that the apparent optimum is a conditional result of the raw-water

chemistry, and that pH, alkalinity and dosage interact in ways that a single-variable test cannot resolve, as the three-factor OFAT analysis of alum coagulation also suggests (Mensah-Akutteh et al., 2022, p. 4).

Compared with these studies, the present investigation provides a descriptive comparison of six PAC dosage levels across five recorded raw-water turbidity conditions. It does not apply RSM, fit a predictive model, or independently validate an optimised operating point. Its contribution is consequently narrower than studies that combine experimental design, multivariable optimisation, and validation. Nevertheless, the observed variation provides a practical basis for identifying where additional experiments are needed to establish a more reliable operating window for PT X.

Implications for PAC Dose Selection and Plant-Scale Injection

The results have practical implications for selecting PAC dosages at PT X. A treatment decision based only on the initial turbidity value may not adequately represent the coagulation response because the observed minimum residual turbidity differed across the five investigated conditions. A more defensible operating procedure would evaluate the current raw-water characteristics, conduct jar tests when conditions change materially, and confirm the selected dose using appropriate treated-water measurements.

The lowest measured residual turbidity should also be distinguished from the economically optimal dose. The current experiment evaluates turbidity removal but does not quantify PAC expenditure, sludge production, residual aluminium, filtration performance, or other operating costs. Consequently, selecting the dose with the lowest recorded residual turbidity does not necessarily identify the most cost-effective treatment condition. An economic optimisation would require additional performance and cost indicators, together with a clearly defined objective function (Krzemiński et al., 2018, p. 1126; Yoo, 2018, p. 1090).

The conversion of laboratory dosage into plant-scale injection flow is another relevant operational consideration. For a fixed raw-water flow rate and a fixed dosing-solution concentration, the required volumetric injection rate is proportional to the nominal PAC dose. Thus, different target doses require different calculated injection rates. This relationship provides a direct mass-balance basis for translating laboratory dosing conditions into preliminary plant operating settings. However, the reported PAC concentration of 10.7% must be verified before the calculated injection flow rate is adopted operationally. If the percentage represents a mass fraction, the density of the commercial solution is required to convert the concentration into a mass-per-volume basis. If it represents an aluminium oxide content or another product specification, the dose basis must also be reconciled. Without this information, the calculated injection rate remains conditional and should not be interpreted as a validated plant setting.

The practical value of the current approach is therefore its integration of jar-test observations with a transparent dosing calculation. This provides a starting point for checking chemical requirements and evaluating alternative operating doses. It does not demonstrate that the calculated flow rate has been implemented successfully or that the predicted performance has been confirmed under continuous plant operation. Field verification would be required to establish whether laboratory-based dosing calculations adequately represent actual hydraulic conditions, chemical delivery, mixing, and clarification performance.

Practical Significance and Potential Operational Benefits

The study provides site-specific evidence that PAC dosage selection should be based on observed treatment performance rather than on an assumed fixed relationship between dose and turbidity removal. For water treatment operations, this approach may support more informed decisions when raw-water quality changes. It can also provide a transparent framework for relating laboratory doses to preliminary chemical-feed calculations. If the findings are subsequently validated under operating conditions, a systematic dose-selection procedure could help operators assess whether the current PAC application is appropriate for the incoming raw water. The potential benefits include improved control of residual turbidity and more rational management of chemical dosing. However, these benefits remain prospective because the study did not compare the existing plant control strategy with a revised strategy, quantify chemical savings, or measure operational performance before and after implementation.

The results should also not be interpreted as direct evidence of environmental or public-health improvements. Although coagulation is an important treatment process, turbidity reduction alone does not establish the removal of all chemical contaminants or pathogens. Evaluation of broader water-quality outcomes would require additional measurements appropriate to the intended water use. In relation to industrial and manufacturing engineering, the study has a limited but identifiable connection to process engineering through experimental parameter selection, performance evaluation, and the calculation of a chemical-feed requirement. Its principal contribution, however, lies in water-treatment process operation rather than in manufacturing technology or manufacturing-system innovation. The results therefore provide a basis for process optimisation in water treatment, but they do not independently establish a substantial contribution to manufacturing science.

Limitations, Robustness, and Future Research

Several limitations affect the interpretation and generalisability of the findings. First, the available dataset contains one reported final-turbidity measurement for each combination of initial turbidity and PAC dosage. Because replicate jar tests were not documented, experimental variability and measurement repeatability could not be quantified. Small differences between recorded values should therefore not be interpreted as statistically significant. Second, the experiment evaluated six dosage levels within a restricted range of 30–42.5 mg/L. The study did not investigate doses below 30 mg/L or above 42.5 mg/L. The results consequently identify the best-performing tested dose for each recorded condition rather than a fully established optimum. This limitation is particularly relevant to the initial turbidity conditions of 27.3 and 30.6 NTU, for which the lowest recorded final turbidity occurred at the highest dose tested. Third, important water-quality variables were not reported, including pH, alkalinity, temperature, and natural organic matter characteristics. The study therefore cannot determine how these parameters influenced the observed dose–response patterns. The absence of

measurements of residual aluminium, sludge production, and filtration performance also limits the assessment of overall treatment effectiveness. Fourth, the reported concentration of PAC used in the plant-scale injection calculation was not explicitly defined on a mass-per-volume or mass-per-mass basis. The calculated injection flow rate is consequently conditional on the assumed concentration basis. Verification of the commercial product specification and density is necessary before the calculation can be used as a confirmed operational recommendation.

Future research should address these limitations through replicated jar tests, a broader dosage range, and controlled evaluation of relevant water-quality parameters. Experimental designs that investigate dosage and pH simultaneously, including RSM where appropriate, could help characterise interactions between operating variables and identify a more defensible operating window. Additional measurements of residual aluminium, settled and filtered turbidity, sludge production, and chemical consumption costs would support a more comprehensive assessment of treatment performance. Finally, the selected operating conditions should be validated using plant data collected across different raw-water conditions. Such validation would help determine whether laboratory responses remain consistent under actual treatment conditions and whether a proposed dosing strategy improves operational performance. Until these steps are completed, the findings should be regarded as an initial site-specific assessment rather than a statistically validated or universally applicable PAC optimisation model.

CONCLUSION

This study evaluated the response of raw water from PT X to six PAC dosage levels under five initial turbidity conditions and examined the implications for plant-scale coagulant dosing. The results showed that PAC reduced turbidity across all investigated conditions, with calculated removal efficiencies ranging from 86.34% to 98.90%. The lowest recorded final turbidity was 0.567 NTU, obtained at an initial turbidity of 51.7 NTU with a PAC dose of 37.5 mg/L. The best-performing tested dose varied across the five initial turbidity conditions, indicating that a single dosage cannot be identified as universally optimal from the available measurements.

The principal contribution of this study is a site-specific assessment of PAC dose–response behaviour combined with a mass-balance framework for estimating the coagulant injection flow rate. The results provide a basis for evaluating dosage selection under the investigated conditions and translating laboratory doses into preliminary plant-scale dosing requirements. However, the reported injection rate of 56.07 mL/s at a dose of 30 mg/L and a raw-water flow rate of 200 L/s remains conditional on interpreting the reported PAC concentration of 10.7% as 107 mg/mL. Verification of the commercial product concentration and its measurement basis is necessary before this estimate can be adopted as an operational setting.

The findings are limited by the absence of reported replicate experiments, the restricted dosage range, and the lack of measurements of pH, alkalinity, and other water-quality parameters that may influence coagulation performance. Future research should incorporate replicated jar tests, evaluate a broader dosage range, verify the PAC solution concentration, and investigate relevant water-quality variables. Field validation under changing raw-water conditions is also required to determine the reliability of the laboratory-based dosing estimates and establish a robust operating strategy for PT X.

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Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT Author Contributions

Ratna Kristina Tarigan: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – review & editing.

Paolo Giovanni Briante: Methodology, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Supervision.

Both authors should review and approve the final manuscript and confirm that the stated contributions accurately reflect their respective roles in the research.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

Ethics approval and consent to participate were not required for this study, as it involved laboratory jar tests using raw-water samples and did not involve human participants or animals.

Code and Software Availability

No custom code or software was developed specifically for this study.

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