THE IMPACT OF COAGULANT TYPE AND DOSAGE ON TURBIDITY AND PH LEVELS IN RAW WATER TREATMENT: A COMPARATIVE STUDY USING THE JAR TEST METHOD AND FULL-SCALE WATER TREATMENT PLANT

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Abstract: The Gajah Mungkur Multipurpose Dam in Wonogiri functions as a source of raw surface water for the surrounding area. This water often contains suspended particles and colloidal substances due to natural processes such as soil erosion, plant decomposition, and microbial activity. This study evaluated three coagulants: Hincolac, PAC 280 Ac, and PAC 250 Ac, at dosages of 60, 70, 80, 90, and 100 ppm. The results of the jar test were compared with those of the full-scale water treatment plant operational test. The findings revealed that the Hincolac coagulant demonstrated superior performance, achieving an efficiency level of 98.60%, which exceeded that of the PAC 250 A and 280 AC coagulants. Hincolac coagulant reached optimal effectiveness at a concentration of 80 ppm, whereas PAC 280 AC and 250 coagulants achieved their highest efficiency at 100 ppm, resulting in turbidity reductions of 98.1% and 97.92%, respectively. Statistical analysis showed that all coagulant types significantly affected turbidity, pH, and floc size ($p < 0.001$). In a comprehensive application, a dosage of Hincolac 67 ± 7.7 ppm was comparable to the tube test method and effectively achieved a 99% reduction in turbidity in the water-treatment output. Elevated alkalinity and Al_2O_3 concentrations significantly influence the effectiveness of coagulant-based water treatment.

Keywords: Surface water; water treatment; coagulant; jar test; full scale application

Abstrak: Bendungan Serbaguna Gajah Mungkur di Wonogiri berfungsi sebagai sumber air baku berbasis air permukaan. Air permukaan sering kali mengandung partikel tersuspensi dan bahan koloid yang dihasilkan dari kejadian alami, seperti erosi tanah, pembusukan tanaman, dan aktivitas mikroba. Studi ini melibatkan tiga jenis koagulan, yaitu Hincolac, PAC 280 Ac, dan PAC 250 Ac, dan menggunakan metode dosis variabel, 60, 70, 80, 90, dan 100 (ppm). Hasil uji jar test dibandingkan dengan hasil uji operasional wtp kapasitas penuh. Hasil studi menunjukkan bahwa koagulan Hincolac menunjukkan kinerja yang lebih baik, mencapai tingkat efisiensi yang tinggi sebesar 98,60% lebih baik dari pada koagulan jenis PAC 250 A dan 280 AC. Koagulan Hincolac mencapai efisiensi tertinggi pada konsentrasi 80 ppm, dibandingkan dengan koagulan PAC 280 AC dan 250 yang dicapai pada konsentrasi 100 ppm, menghasilkan pengurangan kekeruhan 98,1% dan 97,92%. Analisis statistik menunjukkan bahwa semua jenis koagulan memiliki dampak yang signifikan terhadap kekeruhan, pH, dan ukuran flok, dengan nilai p <0,001. Dalam aplikasi skala penuh, dosis Hincolac 67 ± 7,7 ppm sebanding dengan metode uji tabung, dan berhasil mencapai pengurangan kekeruhan 99% pada output pengolahan air. Tingkat kebasaan dan konsentrasi Al_2O_3 yang tinggi memiliki dampak yang signifikan terhadap hasil akhir pengolahan air berbasis koagulan.

Kata Kunci: Air permukaan; pengolahan air; koagulan; jar test; aplikasi skala penuh

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Introduction

The Gajah Mungkur Reservoir Multipurpose Dam, located in Wonogiri, Indonesia, functions as a source of raw surface water. Surface water often contains suspended particles and colloidal substances due to natural processes such as soil erosion, plant decay, and microorganism activity, as well as natural pigments (Skaf et al., 2020; Zhang et al., 2020). With Indonesia's population growth and improved living standards, water demand is rising, driven by the rapid expansion of industry and commerce (Ding et al., 2020; Khan et al., 2019). Indicators of poor water quality include turbidity and discoloration, which result from the presence of colloidal impurities (Aghyani et al., 2023). Coagulants are used to accelerate particle settling. They are crucial in both the coagulation and flocculation stages of water treatment (Adeniyi et al., 2022). In Indonesia, typical water treatment methods include initial sedimentation, coagulation-flocculation, further sedimentation, filtration, and disinfection (Bagastyo et al., 2023). The coagulation-flocculation process is the main technique for effectively separating solid and liquid particles (Yang et al., 2016). This method is employed to eliminate contaminants such as turbidity, colour, microorganisms, natural organic matter, and metallic elements, such as arsenic and radionuclides (Shammas, 2007).

Coagulation and flocculation are crucial stages in water treatment, as they facilitate the aggregation and removal of suspended colloidal particles, organic matter, and other impurities (Wang et al., 2021); (Chen et al., 2024). These steps involve the merging of tiny water particles into larger clusters called flocs, which makes settling easier (Guo et al., 2020). The application of suitable coagulants can improve the effectiveness of the process by lowering turbidity and streamlining the subsequent filtration and disinfection stages (Pirhashemi et al., 2018). Poly-aluminum chloride (PAC), an aluminum-based coagulant, is the main choice for eliminating colloidal particles from untreated water, as highlighted by (Jiao et al., 2015). It is also known for its consistent performance. For water with low turbidity, a higher quantity of PAC is necessary to form dense and easily settling flocs to achieve satisfactory coagulation outcomes (Z. Zhang et al., 2018).

The performance of the PAC is significantly influenced by the basicity and Al_2O_3 concentration. Zhang et al. (2018) suggested that elevated basicity levels and alumina (Al_2O_3) concentrations can enhance coagulation effectiveness. However, contradictory findings also exist, necessitating additional investigations, particularly at the WTP WOSUSOKAS surface raw water sources. The relationship between basicity and Al_2O_3 is crucial for the effectiveness of the WOSUSOKAS WTP water treatment system. Adjusting the basicity and Al_2O_3 levels could be a viable approach for determining the optimal PAC dosage required to enhance the WOSUSOKAS WTP performance while decreasing the risk of metal contamination. This study aimed to identify the ideal PAC dosage, considering different levels of basicity and Al_2O_3 concentration, to effectively decrease the turbidity of surface water from the Gajah Mungkur Reservoir Multipurpose Dam in Wonogiri supplies raw water to the WOSUSOKAS Water Treatment Plant. The PAC performance was assessed at diverse coagulant dosages to identify the most suitable operating parameters for raw water with turbidity levels ranging from low to high concentrations.

The performance of the PAC is notably influenced by its basicity and the concentration of Al_2O_3, as highlighted in earlier research. Studies have indicated that higher levels of basicity and alumina (Al_2O_3) can improve coagulation efficiency. Conversely, some studies present conflicting results, highlighting the need for further investigation, especially concerning the WTP WOSUSOKAS surface water source. The success of the WOSUSOKAS WTP water treatment is also linked to the basicity and Al_2O_3 levels. Modifying the basicity of PAC and Al_2O_3 concentration may help determine the optimal PAC dosage to enhance the performance of the WOSUSOKAS WTP while minimising metal contamination risks. This study primarily aimed to identify the best PAC dose with varying basicity and Al_2O_3 concentrations to lower the turbidity of the Gajah Mungkur Reservoir Multipurpose Dam Wonogiri surface water, which serves as the raw water source for the WTP. The PAC performance was evaluated across different coagulant doses to determine the most effective operational parameters for raw water with varying turbidity levels. The findings were compared in large-scale applications to assess the process performance in both the smallest and largest capacity configurations for clean water treatment.

Materials and methods

General characteristic of the Gajah Mungkur reservoir

The Gajah Mungkur Reservoir, located in the Wonogiri Regency, is an essential source of surface water. Raw water from the Gajah Mungkur Reservoir is pumped from the intake pier to the water treatment plant via a 1.8-km raw water transmission pipeline, as shown in **Figure 1**. The quality of raw water from this reservoir varies significantly, particularly during the rainy season. Generally, physical and chemical parameters, such as temperature, pH, and TDS, remained within acceptable ranges. However, biological and organic contamination is often detected, particularly due to fishing, domestic, and agricultural activities. An examination of the WTP operations from 21 January to 23 January 2025 showed notable variations in raw water turbidity. The turbidity levels of water from the Gajah Mungkur Reservoir fluctuated between 45.6 and 273 NTU, with pH values ranging from 6.8–7.5. High turbidity suggests a large influx of suspended solid materials resulting from surface runoff and erosion in the catchment area during rainfall. In contrast, low turbidity indicates that suspended solids settle within the reservoir before reaching the WTP.

Figure 1. Area of surface water and study (Kementerian PUPR, 2021)

Set-up of jartest

This study aimed to conduct a complete factorial experiment integrating three different coagulant types, each with distinct turbidity levels and dosages. A series of jar tests was performed using six unique experimental setups. The raw water used in these experiments was sourced from the Gajah Mungkur Reservoir. This study monitored turbidity, pH, and floc size as indicators of coagulation performance. Three varieties of polyaluminum chloride (PAC) coagulants were selected for water treatment. The samples included PAC 250 A (Al_2O_3:10%; basicity: 45-55%), PAC 280 AC (Al_2O_3:10%; basicity: 70-80%), and HINCOLAC (Al_2O_3:13%; basicity: 70-80%). These solutions were already in liquid form, negating the need for distilled water for further dilution. A total of 20 liters of raw water samples were collected from the Gajah Mungkur Reservoir under three different weather conditions: heavy rain, light rain, and cloudy sunny conditions. Initial measurements showed that during heavy rain, the turbidity level was 396 NTU, with a pH of 7.4. In contrast, during light rain, the turbidity was 101 NTU, with a pH of 8.0. Under cloudy and sunny conditions, the turbidity and pH were recorded as 86.4 NTU and 7.5, respectively. The study utilized a jar test apparatus was used at room temperature (25 ± 2 °C). The jar test unit, provided by Maskot Flokulator, was equipped with six flat blade stirrers (7.6 × 2.5 cm² each), powered by a 0.05 HP motor with an induction speed range of 10–400 rpm, as shown in

Figure 2. For full-scale application, an Atlanta dosing pump with a capacity of 500 l/h (1 on 1 duty) was used to transfer the coagulant to the injection port in the WTP, as shown in **Figure 3**.

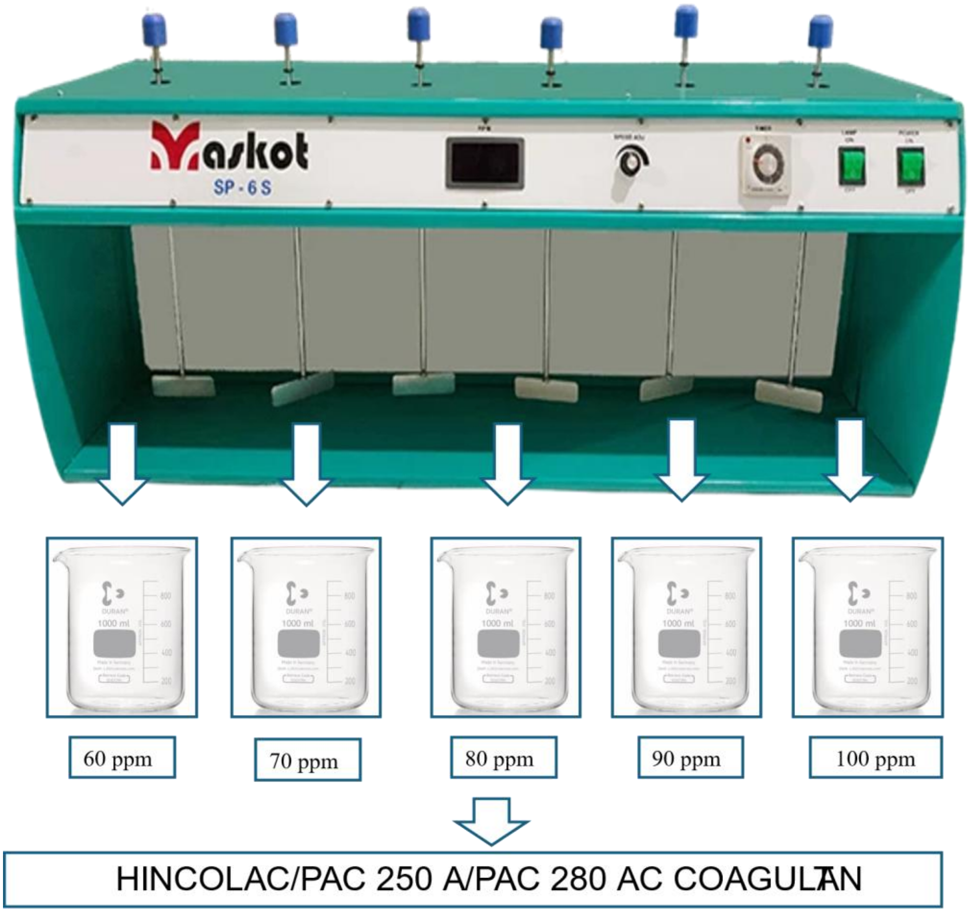

Figure 2. Set up of jar test flocculator

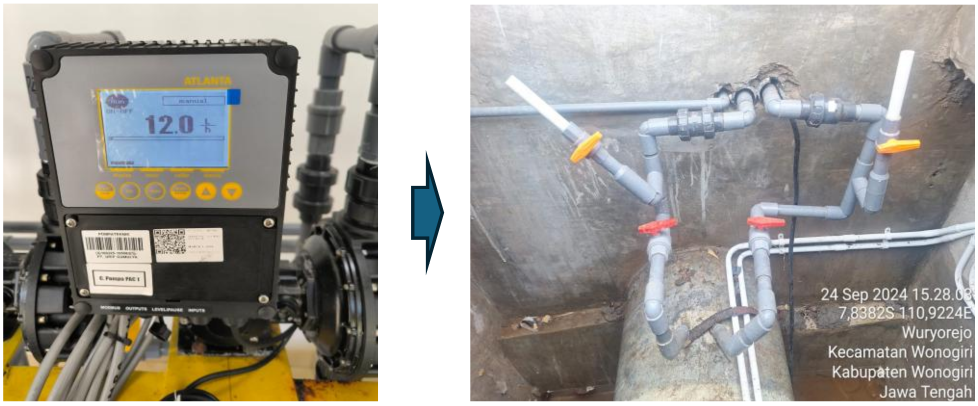

Figure 3. Set up of dosing pump to injection port in full scale application

Analysis methods

Turbidity and pH analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater. The turbidity concentration was determined using an Eutech™ TN-100 Turbidimeter. The pH levels were measured using a digital pH meter (Thermo Fisher Scientific).

Data acquisition

The turbidity performance of chemical coagulation and water treatment processes was investigated. The turbidity removal efficiency in these processes was calculated as shown in **eq. 1.**

$$R\ (\%) = \frac{Ct-Co}{Co}\ x\ 100\% \quad \text{...} (1)$$

where R denotes the removal efficiency, C_0 is the initial concentration in the feed solution (mg/L), and C_t represents the turbidity concentration in the chemical coagulation and water treatment processes (mg/L).

Result and Discussion

Effect of coagulants

The choice of coagulant plays a crucial role in floc development during the clean water treatment process. The study employed PAC 250 A, which contained 10% Al_2O_3 and had a basicity range of 45-55%, PAC 280 AC, also with 10% Al_2O_3 but a higher basicity of 70-80%, and HINCOLAC, which included 13% Al_2O_3 and shared a basicity of 70-80%. Hincolac has a higher aluminum concentration of 13% than PAC 250 A and 280 AC, yet it maintains a similar basicity to PAC 280 AC. The Al_2O_3 concentration in Hincolac exceeded 13%, enhancing its efficiency in reacting with the solution under optimal pH conditions during the chemical separation process. These conditions align with the findings of a joint study. Hincolac demonstrated superior efficiency in reducing turbidity compared to PAC 250 A and 280 AC. The average turbidity of the raw water was 194.47 ± 174.69 NTU. Hincolac's performance was more effective, achieving an efficiency rate of 98.60% and reducing turbidity to 2.71 ± 0.54 NTU, outperforming PAC 250 A and 280 AC, which resulted in turbidity levels of 4.795 ± 0.79 NTU and 3.78 ± 0.73 NTU, respectively. The efficiency levels of the three coagulants were 97.53%, 98.05%, and 98.60% for PAC 250 A, PAC 280 AC, and Hincolac, respectively, as shown in **Figure 5.**

The choice of coagulant influences the final pH of raw water treatment. The use of the coagulant did not significantly change the pH, thus negating the need for the addition of NaOH. Initially, the raw water had an average pH of 7.63 ± 0.32. Following treatment with PAC 250, PAC 280 AC, and Hincolac, the pH levels decreased to 6.84 ± 0.17, 7.12 ± 0.21, and 7.13 ± 0.09, respectively. High basicity levels affect pH reduction efficiency. Moreover, the floc characteristics improved with increasing coagulant basicity, resulting in floc sizes of 0.861 ± 0.18 and 0.729

± 0.28 mm. These sizes are notably different from the 0.586 ± 0.22 mm floc size produced by PAC 250 AC, which has a basicity of 45-55%, as shown in **Figure 6.**

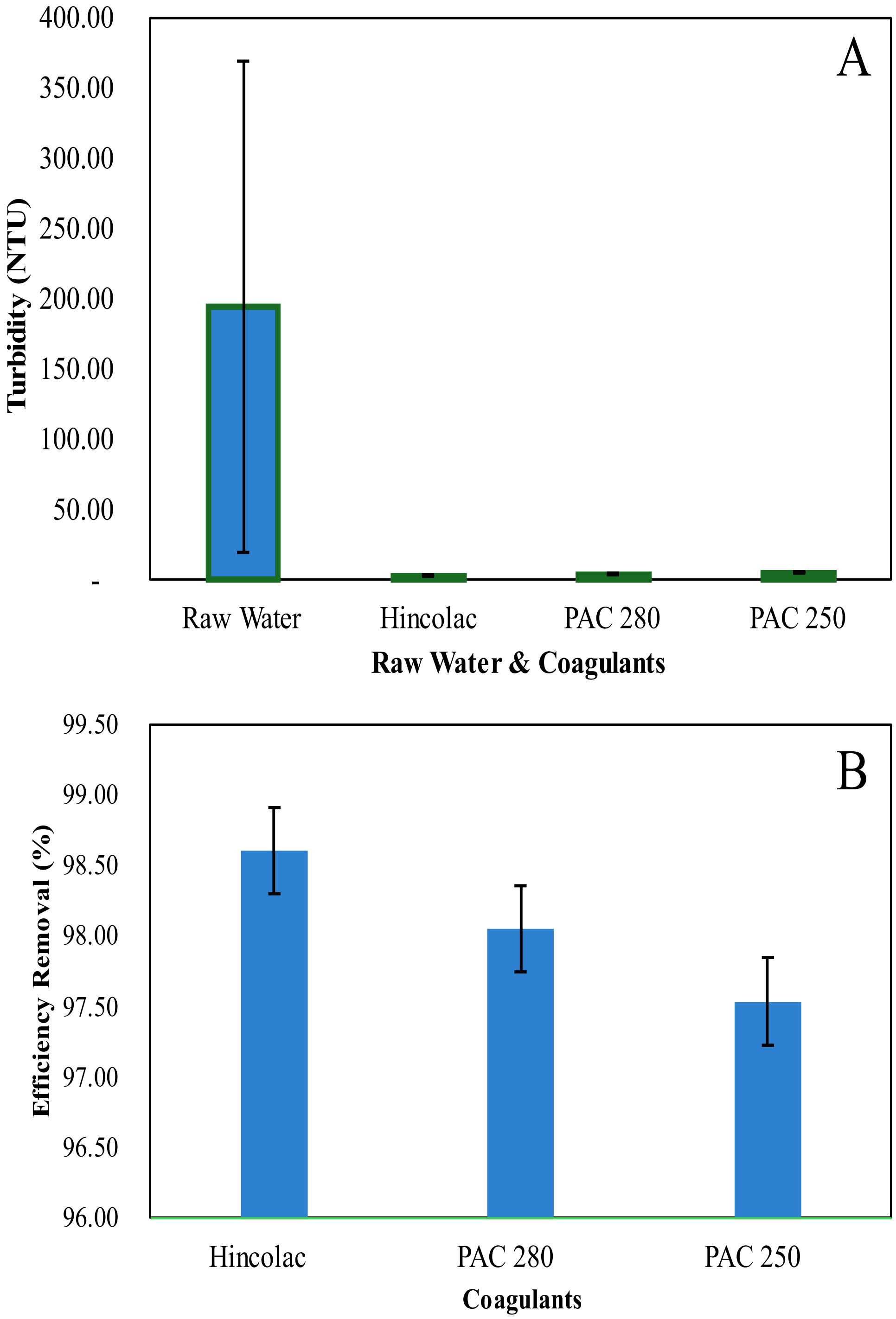

Figure 5. Effect of coagulant for turbidity removal (A: Input and output turbidity after jar test, B: Efficiency removal of Turbidity)

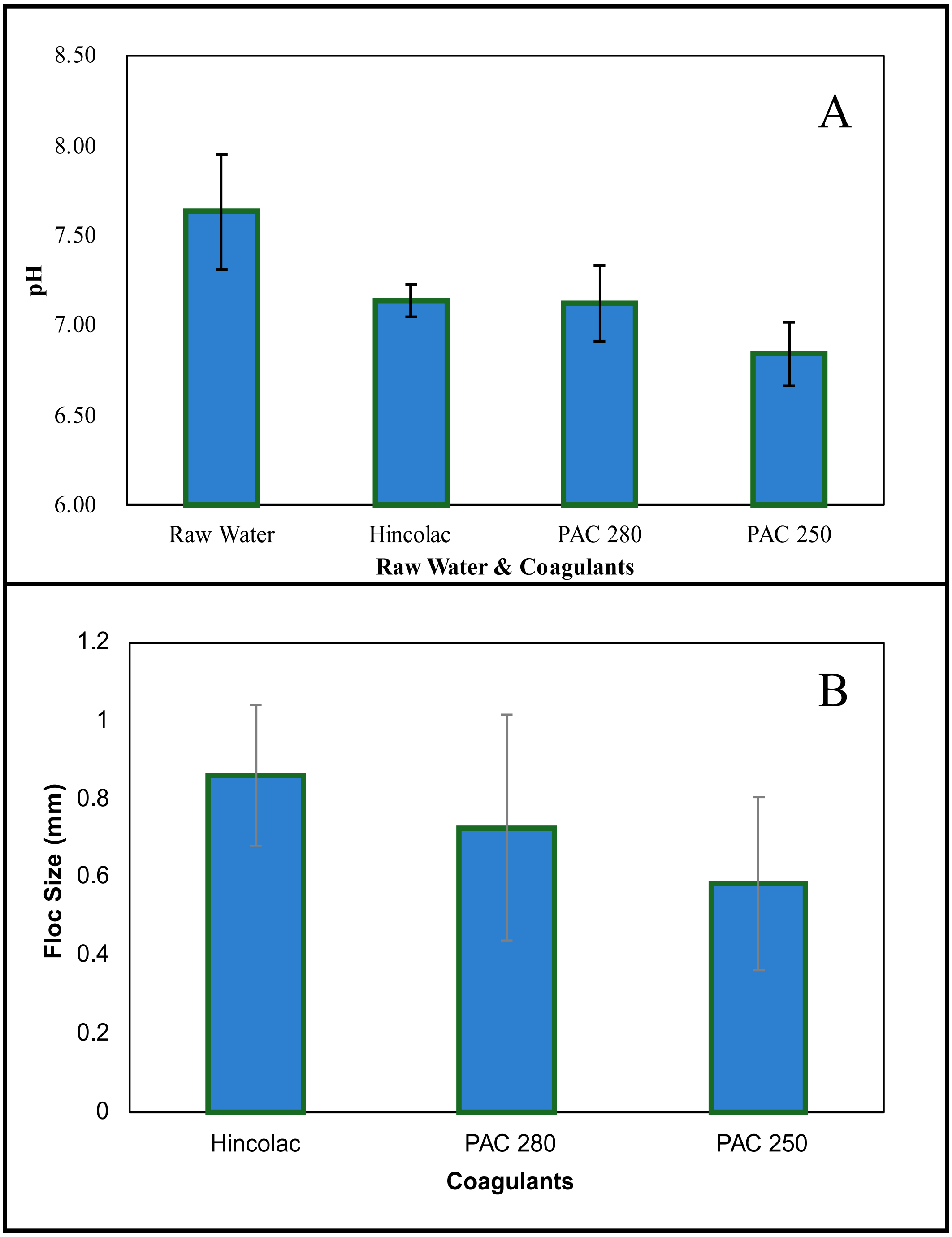

Figure 6. pH and floc size after coagulation process (A: pH after jar test, B: Floc size)

Figures 5 and **6** demonstrate that coagulants with elevated basicity levels significantly influence the effectiveness of turbidity reduction. This pattern was also evident in the comparatively larger floc size, which subsequently affected the settling duration during the sedimentation process, as shown in **Figure 7.**

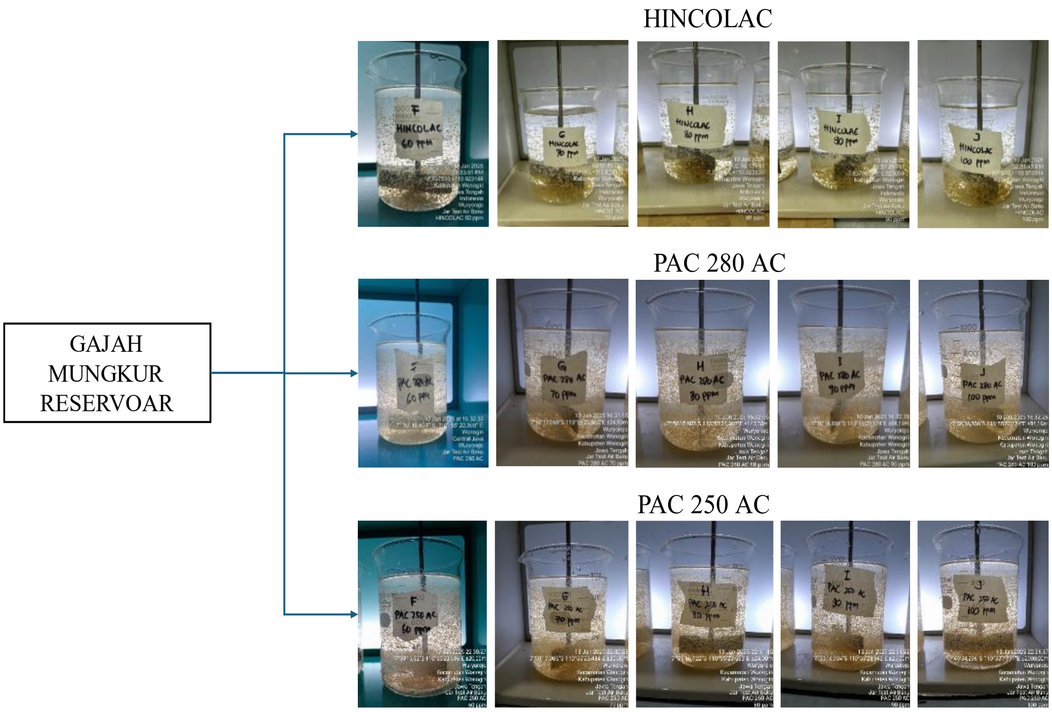

Figure 7. Visual of jar test using Hincolac, PAC 280 AC and PAC 250 AC b

Hincolac coagulant performs optimally when factors such as reduction efficiency, pH value influence, and particle size are considered. As reported by (Smotraiev et al., 2022), increasing the basicity of coagulants enhances the removal rates of TSS and TU, while reducing the OP removal rate from wastewater. Additionally, (Z. Zhang et al., 2018) found that PAC with a basicity of 90.3% and high-viscosity chitosan effectively removed turbidity and NOM, achieving removal efficiencies of about 87%, 63%, and 82%, respectively. This suggests that larger and more stable flocs are likely to form because of the synergistic effect of charge neutralisation. This statement closely aligns with the findings of this study, which identified notable differences in efficiency values and floc size dimensions between coagulants with basicity of 45-55% and 70-80%. The Kruskal-Wallis one-way analysis of variance statistical test revealed that the type of coagulant significantly affected turbidity, pH, and floc size output values, with a p-value of less than 0.001, indicating a significant impact of all coagulant types on reducing the turbidity, pH, and floc size. The Tukey Test showed significant differences between pH and floc size, as well as between floc size and coagulant type. A significant difference was also observed between the turbidity and floc size. However, no significant differences were observed between pH and turbidity, turbidity and coagulant type, and coagulant type and floc size.

Effect of dosage coagulants

In the chemical coagulation process, the coagulant dosage is a vital consideration, especially during raw water treatment. This study evaluated the performance of coagulants, namely PAC 250 A (with 10% Al_2O_3 and a basicity

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range of 45-55%), PAC 280 AC (with 10% Al_2O_3 and a basicity range of 70-80%), and HINCOLAC (with 13% Al_2O_3 and a basicity range of 70-80%), through jar tests at coagulant doses of 60, 70, 80, 90, and 100 ppm for each type. Hincolac coagulant demonstrated the highest efficiency at 80 ppm, achieving 98.7% efficiency, or 2.5 ± 0.26 NTU. Conversely, PAC 280 AC and 250 coagulants reached their optimal performance at 100 ppm, resulting in 98.1% and 97.92% turbidity reduction, with NTU values of 3.46 ± 0.81 and 3.82 ± 0.99, respectively. As depicted in Figure 6, the Hincolac coagulant showed a more consistent turbidity reduction than PAC 280 AC and PAC 250 AC, as illustrated in **Figures 8** and **9**. The Al_2O_3 content in Hincolac also had a higher basicity value, which was 13% greater than that of the two PAC coagulants. The differences in coagulant basicity and Al_2O_3 concentration strongly influence the effectiveness of organic matter removal. Prior to coagulation, an increased H^+ concentration (lower pH) enhances removal efficiency, which is inversely related to coagulant basicity (Yang et al., 2010); (Sperczyńska et al., 2016).

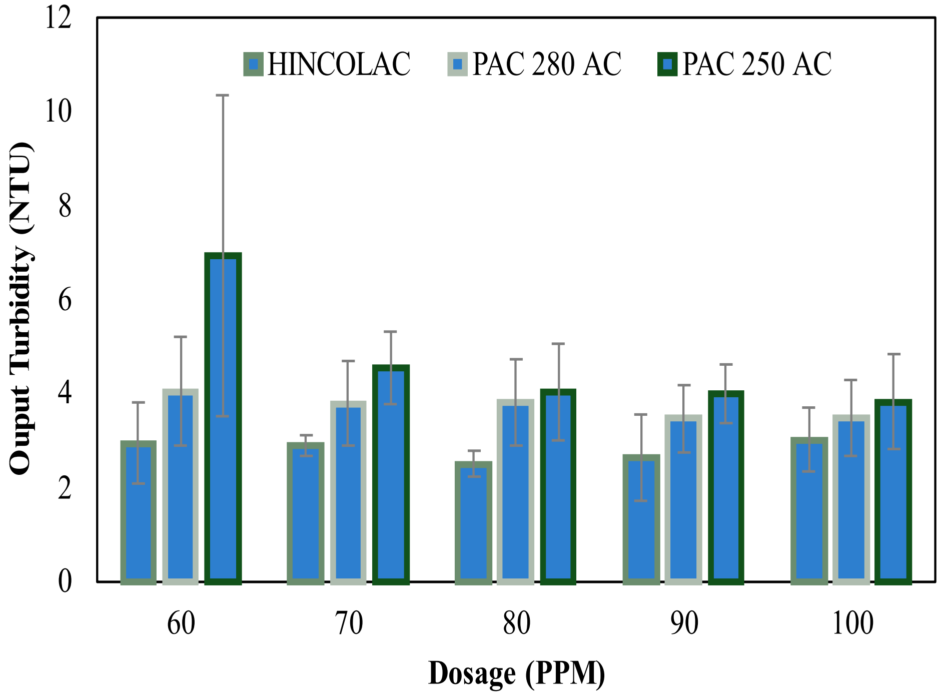

Figure 8. Output turbidity during jar test of Hincolac, PAC 280, and 250 AC

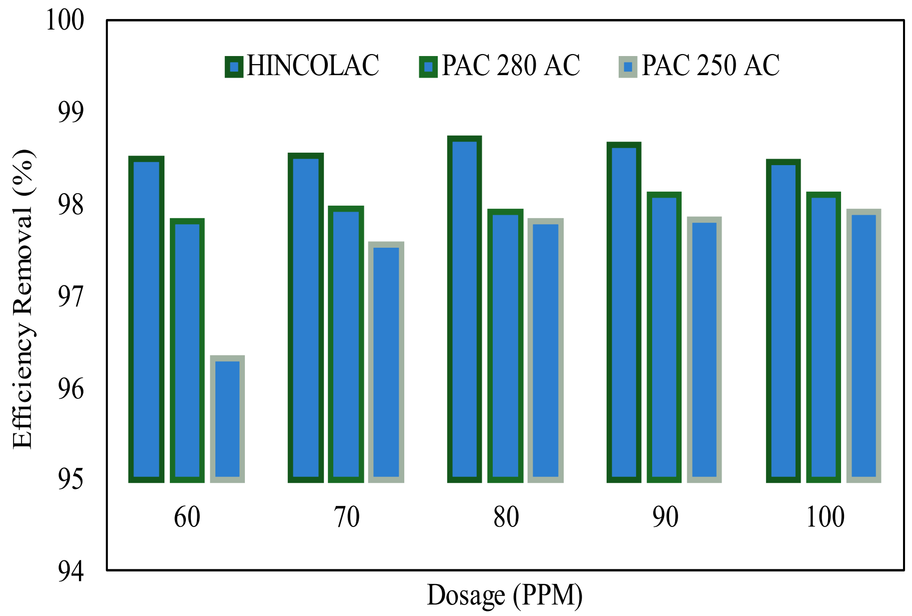

Figure 9. Efficiency removal of turbidity during jar test of Hincolac, PAC 280, and 250 AC

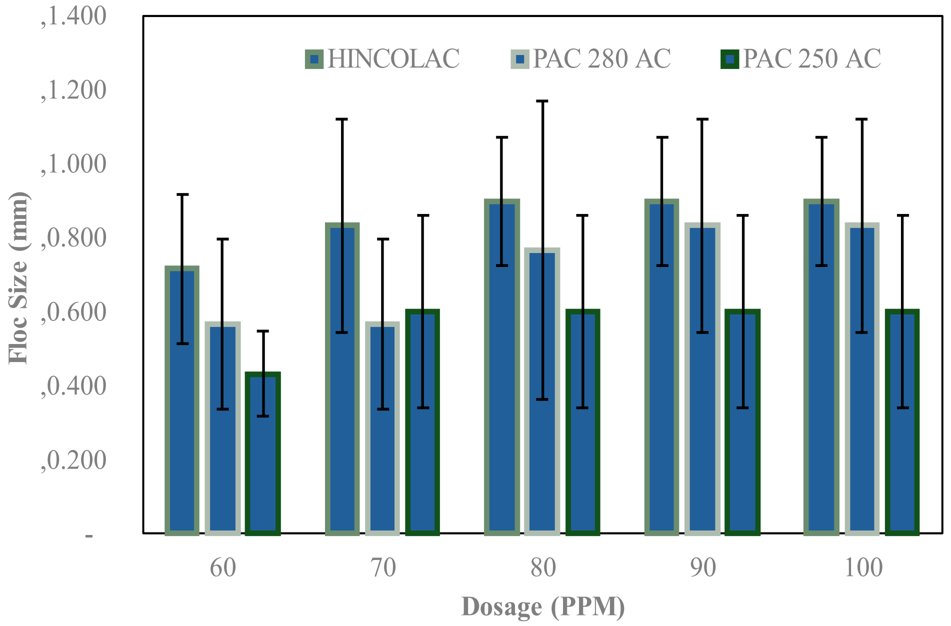

Figure 10. Floc size during jar test using Hincolac, PAC 280, and 250 AC

Figures 8 and **9** suggest that a 60 ppm dose of Hincolac coagulant achieves optimal efficiency compared to a PAC coagulant, which requires a dose of up to 100 ppm. A statistical test was performed to assess the impact of dosage on turbidity. Spearman rank-order correlation analysis revealed a significant link between dosage and floc size, showing that higher dosages were associated with larger floc formation. Additionally, turbidity exhibited a strong and significant negative correlation ($p < 0.001$), indicating that larger floc sizes corresponded to higher turbidity. This finding aligns with **Figure 10**, which shows that Hincolac produced larger flocs than PAC 280 and 250 AC. Consequently, only floc size was significantly affected by dosage and was closely linked to turbidity reduction, whereas pH did not significantly influence the relationship between these variables. The results indicated a linear relationship between variations in turbidity and the average size of flocs. Larger flocs produced during the jar test led to a faster sedimentation rate and decreased residual turbidity, supporting the findings of (Lin & Ika, 2019); (Saritha et al., 2017); Cheng et al.,2011).

Performance of full scale WTP

Hincolac coagulants are highly effective in reducing turbidity, maintaining a consistent pH, and generating superior flocs. These findings will serve as the main basis for implementing a large-scale raw water treatment process at a rate of 3 x 250 liters per second. A pump with a capacity of 3 × 500 L/h was employed to continuously deliver the coagulant over a 24-hour period. The treatment process led to a significant 99% reduction in the turbidity levels in the output filtration and reservoir. The turbidity of the treated raw water was 100.6 ± 46.34 NTU. After Hincolac addition, the water output in sedimentation units I and II displayed turbidity levels of 3.59 ± 5.03 NTU and 2.29 ± 3.99 NTU, respectively (Figure 11). Post-dosing, the actual pH level remained largely stable, recorded at 6.94 ± 0.17 at the outlet of sedimentation basin II (Figure 11). These conditions align with the jar test results, which utilised a Hincolac dose of 67 ± 7.7 ppm throughout the process.

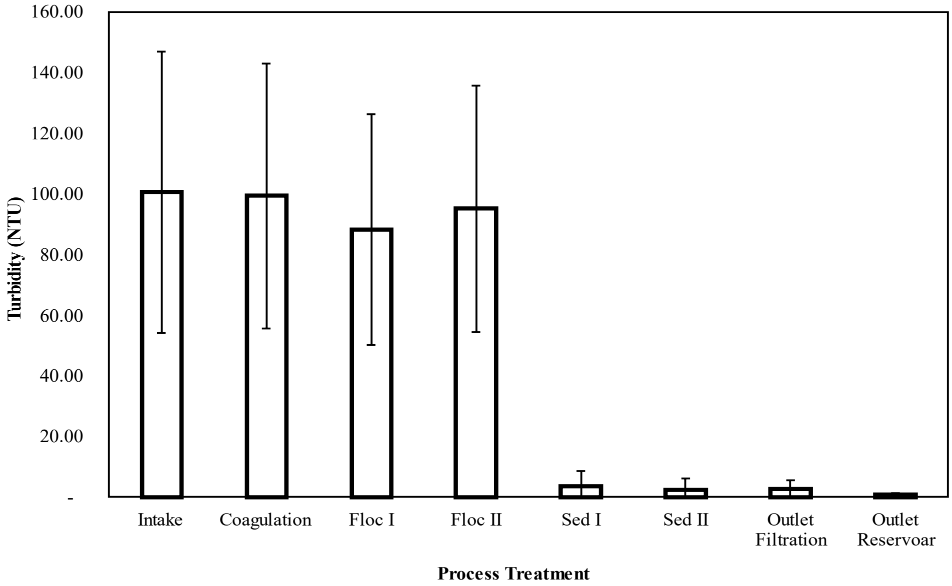

Figure 10. Performance test of chemical hincolac in turbidity removal in full scale

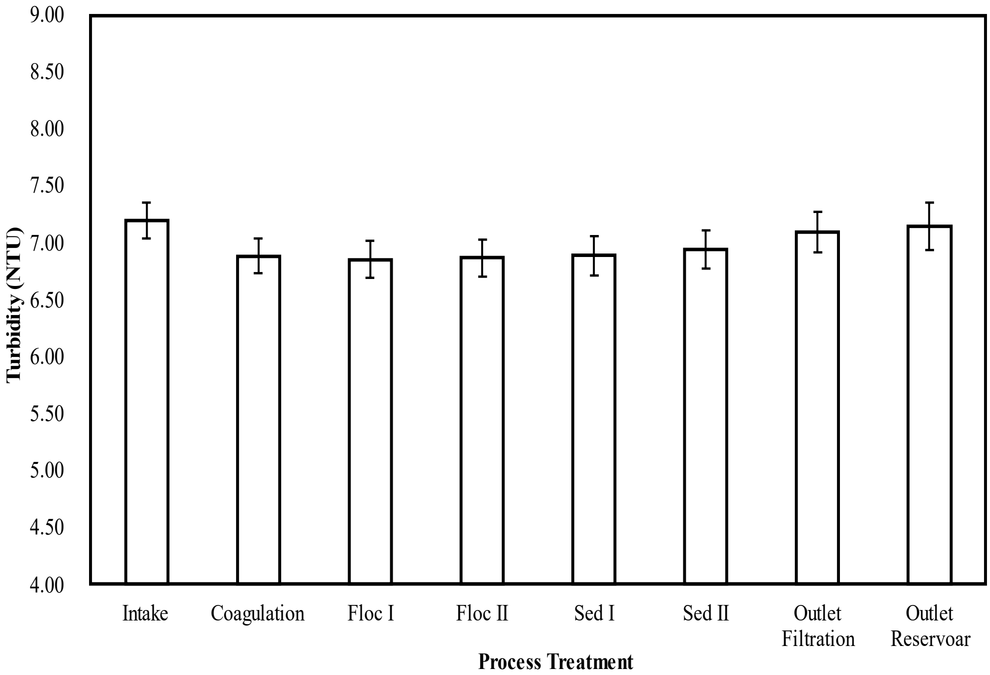

Figure 12. Performance test of chemical hincolac in pH in full scale

As illustrated in **Figure 12**, the turbidity and pH of the raw water source exhibited significant variability. This situation can lead to process instability if the coagulant concentration, including the aluminum content and basicity level of the coagulant type used, is not sufficiently high. Hincolac coagulants can maintain stability in the fluctuating values of incoming raw water during processing. Coagulants with high basicity are generally more stable and effective under fluctuating raw water conditions because they can better buffer pH, form flocs more quickly and robustly under variable conditions, and reduce the need for constant dosage adjustments. According to recent studies (Z. Zhang et al., 2018); (Y. Chen et al., 2020); (Lapointe et al., 2021); (Saxena & Brighu, 2020), higher-basicity polyaluminum chlorides (PACs), characterized by a higher proportion of colloidal and polymeric Al species and a lower proportion of monomeric Al species, enhance the removal of turbidity and natural organic matter (NOM) while effectively controlling residual aluminum levels. The process results show that using a Hincolac-type coagulant achieves a safe residual aluminum concentration of 0.04 mg/L, which is within the acceptable standard of 0.2 mg/L. In terms of aluminum reduction efficiency, the process achieved a reduction rate of 78.94% from an initial value of 0.19 mg/L. The development of coagulation processes using chemicals in raw water treatment is essential, whether employing organic coagulant-based processes using chitosan (Yang et al., 2016) or electrochemical coagulation-based processes using tubular models (Y. Zhang et al.,2020) developed continuous-flow models based on multi-rod helical systems (Hamdan & El-Naas, 2014); (Ardhianto

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et al., 2024), or integrating them with solar PVs to help reduce chemical consumption and sludge during the treatment process.

Conclusion

The water in the Gajah Mungkur Reservoir is characterised by significant turbidity, requiring coagulants with high aluminum content and basicity for effective raw water treatment. The jar test method was employed to determine the optimal coagulant dosage. Coagulant concentrations of 60, 70, 80, 90, and 100 ppm were tested using Hincolac, PAC 280 AC, and PAC 250 AC coagulants. The jar test results revealed that Hincolac coagulants were the most effective, achieving an efficiency rate of 98.60%%and reducing turbidity to 2.71 ± 0.54 NTU. This performance surpassed that of PAC 250 A and 280 AC, which resulted in turbidity levels of 4.795 ± 0.79 NTU and 3.78 ± 0.73 NTU. The efficiency rates for the coagulants were 97.53% for PAC 250 A, 98.05% for PAC 280 AC, and 98.60% for Hincolac. Hincolac reached peak efficiency at an optimal concentration of 80 ppm, achieving a maximum efficiency of 98.7%, corresponding to a turbidity level of 2.5 ± 0.26 NTU. The optimal dosing levels for PAC 280 AC and 250 coagulants were 100 ppm, resulting in turbidity reductions of 98.1% and 97.92%, with turbidity values of 3.46 ± 0.81 and 3.82 ± 0.99, respectively. Statistical analysis indicated that all coagulant types significantly affected turbidity, pH, and floc size ($p < 0.001$). Testing in a full-scale water treatment plant showed that the selected coagulants achieved the same turbidity efficiency, with a 99% reduction in turbidity at the plant-process output. However, further research is necessary to assess the effectiveness of coagulants under rainy conditions, where high turbidity levels and increased dosages are involved.

Conflict of Interest

The authors declare no competing financial interests or personal relationships that could influence the work reported in this study.

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