

Original Research Article

Batik Wastewater Treatment: Performance of Combination PAC with Hydrocyclone Separation

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Abstract

Batik wastewater contains high levels of total suspended solids (TSS) and turbidity, making it difficult to decompose naturally. To prevent environmental pollution, this study investigated a treatment method that combined coagulation in a mixing tank and flocculation using a hydrocyclone. Polyaluminum chloride (PAC) was used as the coagulant. The coagulation process was tested at stirring speeds of 100–140 rpm and coagulant doses of 150–300 mg/L. The results showed that a coagulant dose of 300 mg/L and a stirring speed of 140 rpm achieved the highest removal efficiencies: 95.45% for TSS and 95.24% for turbidity. A two-way analysis of variance (ANOVA) confirmed that the coagulant dose significantly affected removal efficiency ($p=0.049$), whereas the stirring speed did not have a significant effect ($p=0.77$). Furthermore, particle size analysis (PSA) and zeta potential tests indicated that the PAC coagulant successfully destabilized the suspension in the wastewater, leading to the formation of large aggregates and accelerating the separation process. Overall, these results indicate that combining a coagulation mixing tank with a hydrocyclone flocculation unit offers an efficient and rapid solution for treating batik wastewater.

Keywords: Batik wastewater; hydrocyclone; polyaluminum chloride (PAC)

1. Introduction

Wastewater produced from batik encompasses a wide range of contaminants, including synthetic dyes, waxes, detergents, and binders, which are present in concentrations above the allowable limits set by environmental regulatory agencies (Andrianto & Suwardiyono, 2016). One of the characteristics of batik wastewater is that it has a high pH and a low biological/chemical oxygen demand ratio, which can lead to the near-complete destruction of organic material before being discharged into the environment (Muqim and Purnomo, 2023). Wastewater contains many pollutants, which often poses a challenge for micro, small, and medium-sized enterprises (MSMEs) in the batik industry that rarely have wastewater treatment units for their production (Islam and Mostafa, 2020). The composition of dyes used in the production of batik should be effective in removing total suspended solids and other parameters, such as color and turbidity (Daud et al., 2022).

Insoluble organic pollutants contained in batik wastewater can be removed using a physicochemical method, namely, coagulation-flocculation (Daud et al., 2023). Recently, coagulation-flocculation has been widely used because of its simplicity and low cost (Zaharia et al., 2024). The basic coagulation-flocculation process involves rapid stirring followed by the addition of chemical coagulants. This treatment destabilizes suspended particles and colloids to change suspended particles into microflocs with the assistance of coagulants, thereby removing suspended particles before entering the next treatment stage. Although conventional coagulants, such as aluminum sulfate, are commonly used because of their effectiveness, there are other popular options, such as polyaluminum chloride (PAC). PAC is known to be effective for low doses, has a wide pH range, and can produce flocs with high-density characteristics, which can minimize sludge production (Varank et al., 2021; Islam and Mostafa, 2020).

Traditionally, coagulation-flocculation is performed in mechanically agitated vessels. Although such systems can attain up to 95% removal efficiency, they are limited by intricate designs, high consumption of electricity, and substantial land area requirements (Chatila and Danageuzian, 2022). In comparison to this method, hydrocyclones solid-liquid separation provides a small footprint that is continuous and does not require much maintenance, exploiting centrifugal forces to concentrate denser particulate matter, thereby removing the requirement for large settling tanks (Liu et al., 2024). Fluid enters the unit tangentially, creating a radial pressure gradient and swirl flow within it that induces a centrifugal force on solid particles towards the wall, down to the underflow, while clarified water migrates toward the central internal vortex exits via overflow (Cavalcante et al., 2024).

Coagulation with PAC, followed by hydrocyclone separation, has become a promising pretreatment option for improving TSS and turbidity removal, making the system feasible for MSMEs, where space is a constraint (Lee and Lee, 2019; Zelif et al., 2021). The present study was framed to optimize a hydrocyclone unit for the coagulation-flocculation process by varying the PAC concentration and mixing speed. The operating conditions that result in stable (i.e., settleable) flocs will be identified, along with simple adjustments that can be recommended for on-site implementation.

2. Methods

2.1 Sampling method

Wastewater was collected from the major drain of a medium-scale batik industry located in the Batik Industrial Area, East Java. Samples were collected from two stages: color washing and wax removal, as these are the major sources that contain high concentrations of dyes, waxes, and surfactants. We collected 1 L grab samples on ten different occasions with three replicates per sampling event, resulting in a total of 30 samples ($n = 30$).

2.2 Physicochemical analysis

The first conclusions on wastewater characterization were addressed to the TSS and turbidity. TSS was conducted by gravimetric refer to National Standard Method (SNI 6989.3-2019) detection ranges of 4 mg/L up to 20,000 mg/L. Turbidity was generated with digital turbidimeter refer to National Standard Method (SNI 06-6989.25) and represented in the forms of NTU. After testing for efficiency, the particle size distribution and zeta potential of treated water were determined with a Cordouan Amerigo Nanoparticle Size & Zeta Potential Analyzer at 24°C; these analyses were carried out on representative samples (i.e., those showing less-than-ideal settling behavior) to explore the mechanisms of colloid stability and floc formation limitations. However, the determination of optimum operational conditions relied primarily on the highest separation efficiency data (TSS/turbidity removal).

2.3 Mechanical coagulation

Jar-tests for mechanical dispersion were performed with a standard jar-test device. A PAC stock solution was added to attain the final concentration of 150, 200, 240 and 300 mg/L. The mixing speed for each experiment were set at three different values such as 100 rpm, 120 rpm and 140 rpm respectively.

2.4 Hydrocyclone separation

The experimental hydrocyclone unit had a nominal diameter of 15 cm. The geometric parameters were inlet width, 10 mm; cone angle, 20°; vortex finder diameter, 30 mm; underflow orifice diameter, 10 mm; and overflow diameter, 30 mm. The coagulation effluent was pumped into the hydrocyclone at a continuous feed rate of 9 L/min with a feed pressure of 138 kPa (approximately 14.1 m head). The unit was operated continuously until a steady state was achieved, and effluent samples were collected after 60 min. A visualization of the reactor hydrocyclone is shown in Figure 1.

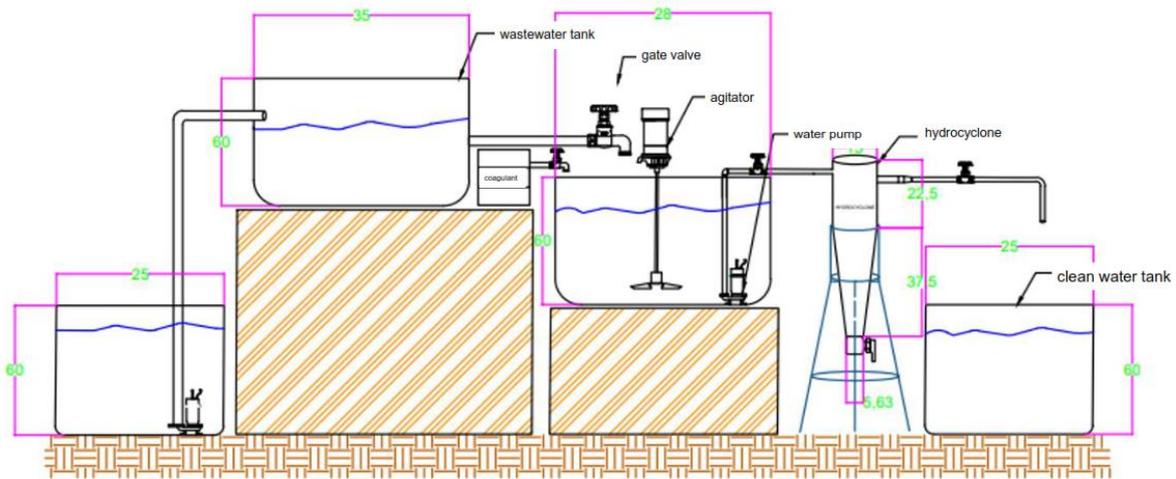


Figure 1. Experimental setup of the hydrocyclone pretreatment unit for batik wastewater treatment

2.5 Statistical analysis

Turbidity and TSS data were analyzed using two-way analysis of variance (ANOVA) with coagulant concentration (four levels) and mixing speed (three levels) as fixed factors. All statistical analyses were performed using Minitab 21, and differences were considered significant at $\alpha = 0.05$.

2.6 Quality assurance

Samples were placed into pre-cleaned glass bottles with airtight seal caps to avoid contamination. Laboratory analysis was done maintaining all safety habits, including PPE usage, such as lab coat and nitrile gloves.

Table 1. The quality of batik wastewater samples

No	Code	Parameter		
		pH	TSS (mg/L)	Turbidity (NTU)
1.	Sample A (Raw wastewater)	9	>100	>50
2.	Sample B (After Coagulation)	7.4	45	18
3.	Sample C (After Hydrocyclone)	7.2	12	6

3. Results and Discussion

3.1 Effect of PAC Dosage and Mixing Speed on Removal Efficiency

3.1.1 Total Suspended Solids (TSS) Removal

The removal efficiency of TSS was significantly affected by both the chemical dosage and mixing speed. As shown in Figure 2, a positive relationship was noted, wherein the removal efficiency increased with increasing coagulant dosage and mixing speed. The lowest removal efficiency of 42.86% was obtained at the lowest operating conditions of 150 mg/L PAC and 100 rpm, whereas the highest removal efficiency of 95.45% was obtained at the highest experimental conditions of 300 mg/L PAC and 140 rpm.

The results were found to be statistically significant with two-way analysis of variance (ANOVA), with a p-value of < 0.001 for the dosage of the coagulant and 0.049 for the mixing speed. Since both values are less than the significance level ($\alpha = 0.05$), it can be said that there is statistical evidence that both factors affected the separation process. The model had a high coefficient of determination ($R^2 = 0.9676$), indicating that 96.76% of the variation in TSS removal could be explained by the variables in the experiment, and only 3.24% could be explained by error.

Since the coagulant dose and mixing rate have been shown to have a significant impact on TSS removal, a Tukey post-hoc test was conducted (Figures 3 and 4). The coagulant dose was found to be the most important variable in terms of removal efficiency. The Tukey test showed significant differences in the pairs 200–150 mg/L, 300–150 mg/L, and 300–200 mg/L. The fact that the confidence intervals for these pairs did not cross zero confirms that the removal efficiency is significantly dependent on the chemical dose. At a dose of 150 mg/L, the concentration of available cationic groups may have been too low to neutralize the anionic charge completely, whereas a dose of 300 mg/L was sufficient to create large aggregates with high density, which could be separated by the centrifugal forces of the hydrocyclone (Mustereş et al., 2021; Liu et al., 2024).

Regarding mixing speed, although the ANOVA showed a significant effect ($p = 0.049$), the Tukey test showed that there was no significant difference between the speeds ($p = 0.77$), as all confidence intervals contained zero. This implies that while the mixing speeds were significant in explaining the variance in the model, their significance was negligible in comparison to the highly significant effect of the coagulant dose. The high density of the chemical flocs produced by the PAC would have inhibited floc breakage, which is normally observed at high mixing speeds for conventional alum flocs (Yu et al., 2011).

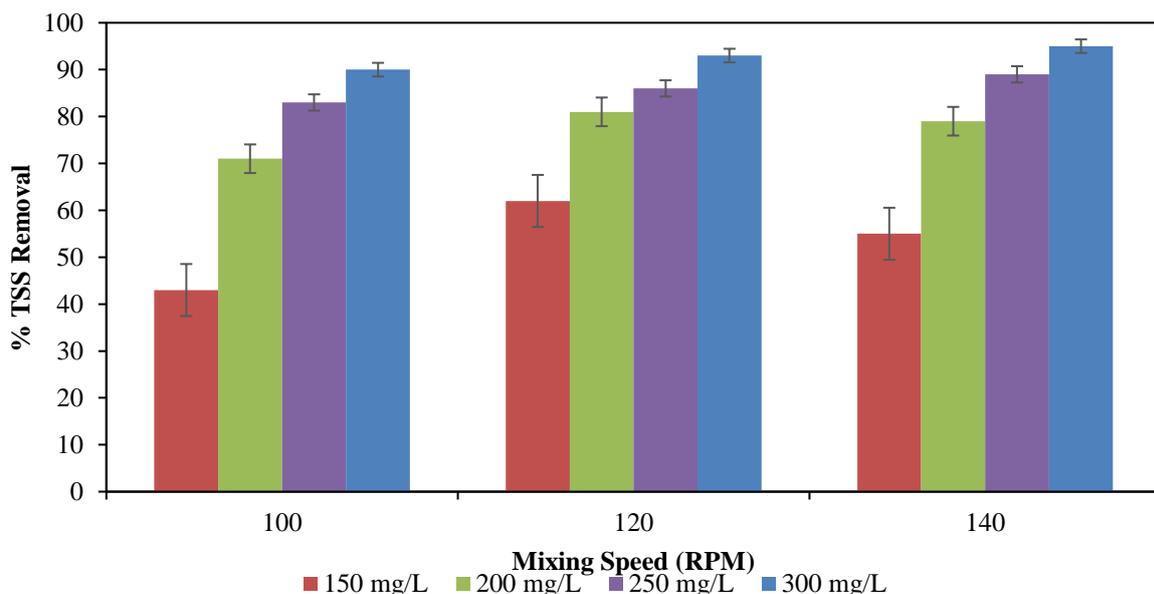


Figure 2. Effect of mixing speed and coagulant dosage on the percentage of TSS removal

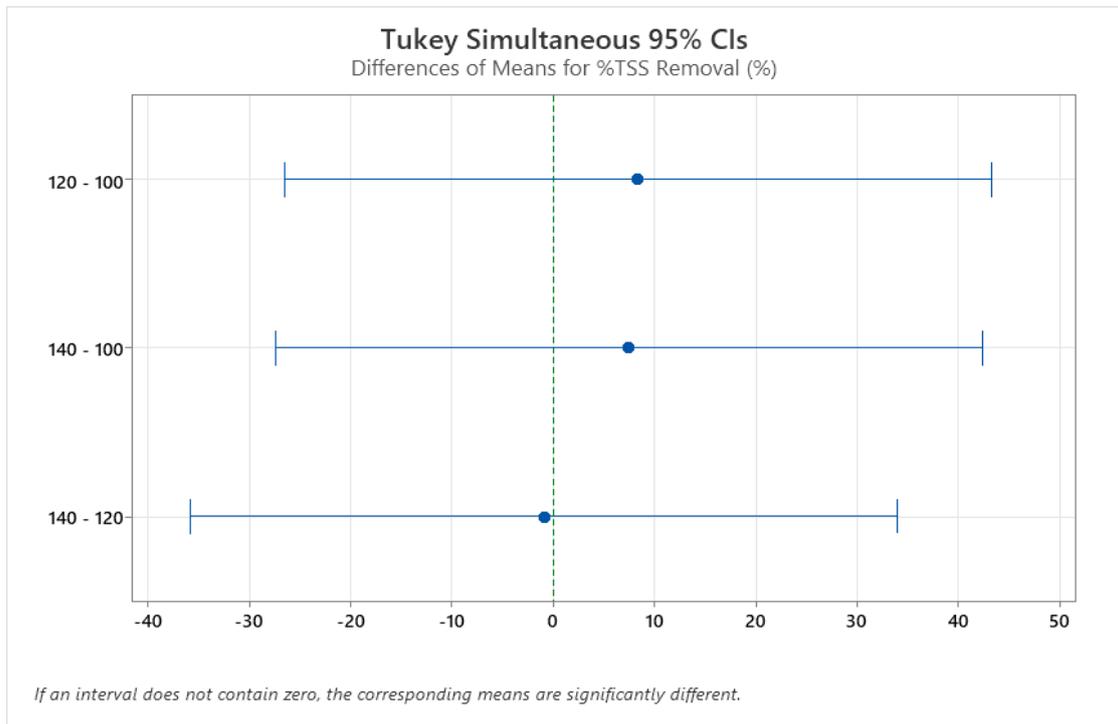


Figure 3. Tukey post-hoc analysis of mixing speed effects on TSS removal

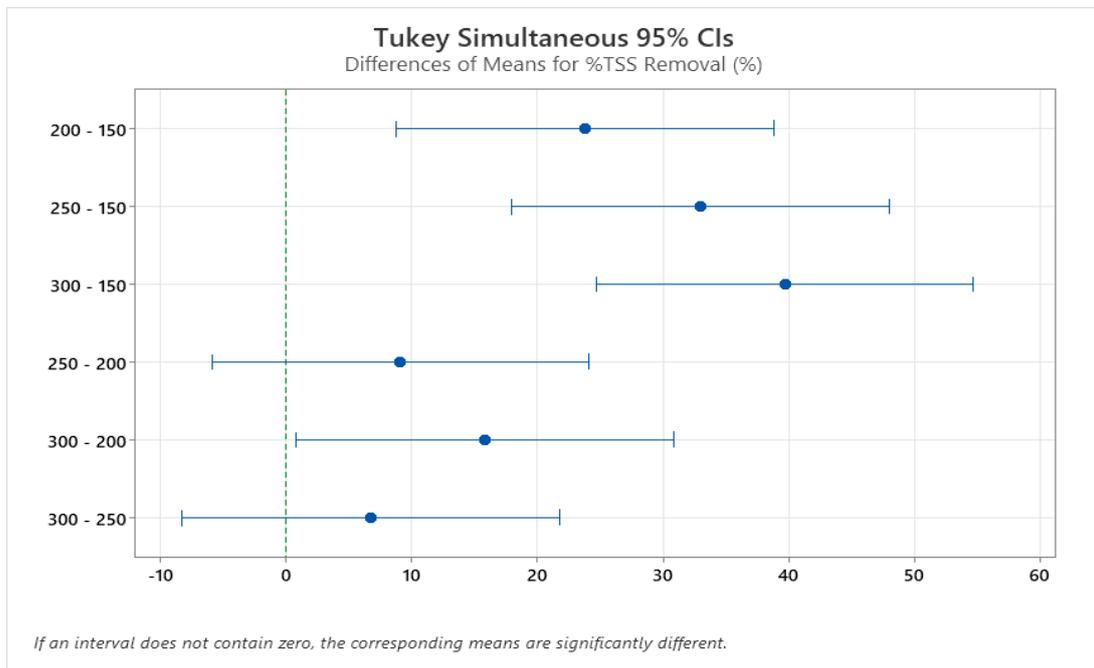


Figure 4. Tukey post-hoc analysis of coagulant dosage effects on TSS removal

3.1.2 Turbidity Removal

Turbidity, which is a surrogate measure for colloidal stability, exhibited a slightly different trend than TSS. As shown in Figure 5, the lowest turbidity removal of 67.23% was at 150 mg/L and 120 rpm, whereas the highest removal was achieved at the same optimal TSS conditions of 300 mg/L.

Two-way ANOVA for turbidity showed that only coagulant dosage was significant ($p = 0.007$), whereas mixing speed was not significant ($p = 0.27$). The analysis showed an R^2 of 0.8592, indicating that 85.92% of the variation in turbidity removal could be explained by the variables in the experiment. This difference is significant because it indicates that, while mixing helps in the creation of large flocs (TSS), the removal of turbidity is mainly dependent on chemical rather than physical processes.

The results of the Tukey post-hoc analysis validated that the enhanced removal of turbidity was directly caused by the addition of more materials (i.e., dosage) at higher dosages. For instance, moving from a dosage of 150 to 300 mg/L produced substantially greater turbidity removal, as indicated by confidence intervals that did not overlap with zero (Figure 6).

The effectiveness of mixed processes for 150 mg/L solids is supported by the evidence of lower speeds (100 rpm) outperforming moderate speeds for flocculation performance (100 rpm = 71.91%; moderate speed = 67.23%). Although PAC produces strong, cohesive, and non-cohesive/weak flocs, as provided in Section 5 (TSS), the strengths of the flocs produced at lower levels of PAC are weaker in comparison. At this point, a high mixing speed can easily break down these weak flocs, thereby redispersing them as fine particles and thus increasing the turbidity (Aragaw and Bogale, 2023). This result further supports that in this research, turbidity removal was more affected by floc breakage than TSS removal.

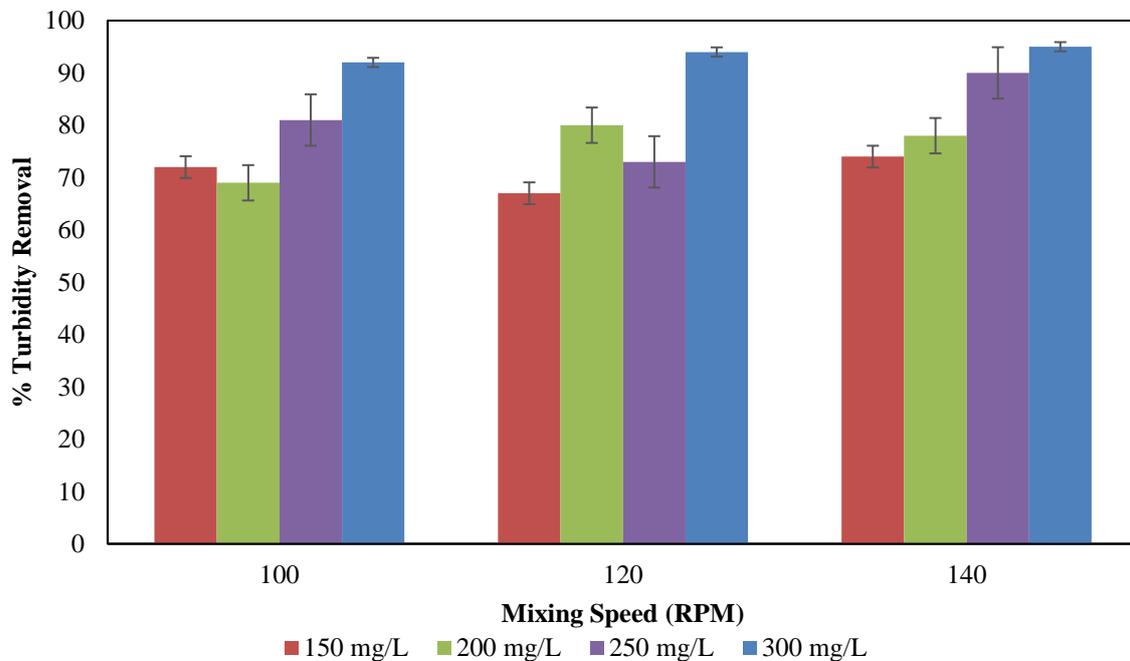


Figure 5. Effect of mixing speed and coagulant dosage on the percentage of turbidity removal

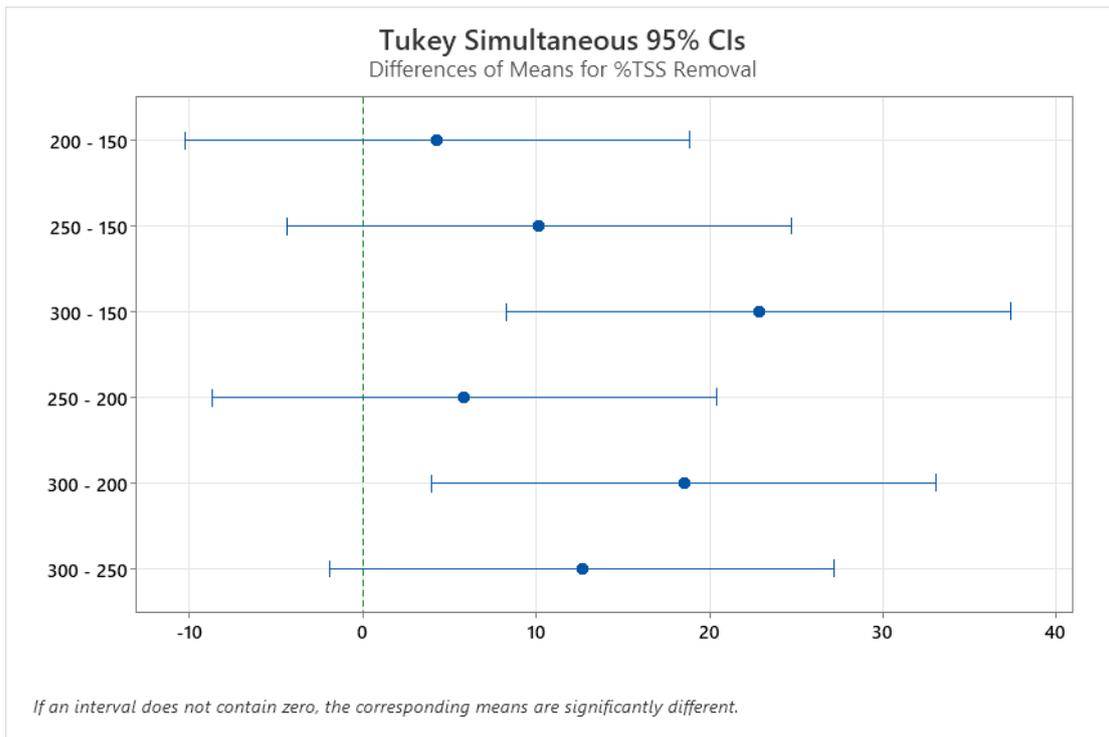


Figure 6. Tukey post-hoc analysis of coagulant dosage effects on turbidity removal

3.1.3 Mechanism of Particle Aggregation and Centrifugal Separation

To explain the high removal efficiencies reported in Figures 2 and 5, a multi-stage mechanism is proposed. The process involves three distinct phases: chemical destabilization, physical aggregation, and centrifugal separation (Figure 7).

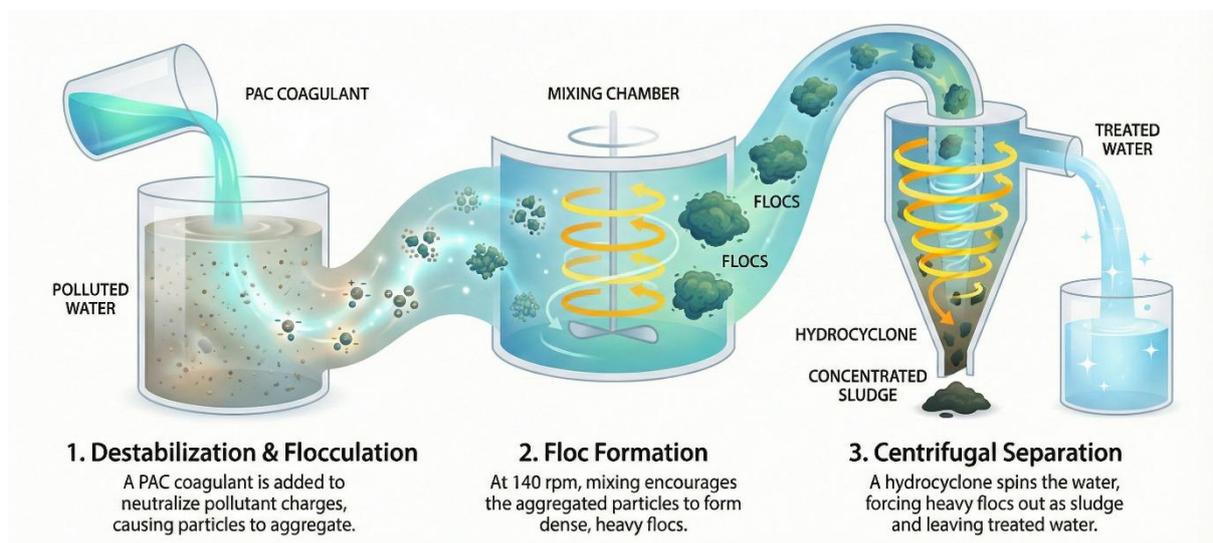


Figure 7. Schematic representation of the PAC-hydrocyclone mechanism

In the initial stage, PAC functions as a destabilizing factor. Batik wastewater is normally stable because of the negative surface charge of pollutants. When PAC was added at an optimal concentration of 300 mg/L, aluminum-based cations were introduced to neutralize the charges (Islam and Mostafa, 2020). According to Islam and Mostafa (2020). PAC is most effective in textile wastewater treatment because of the pre-hydrolyzed form that reduces the zeta potential more effectively than conventional alum. Moreover, at this concentration, aluminum hydroxide precipitates were generated by PAC, which

trapped small particles as they settled. This process of sweep flocculation is still the most prominent in the removal of high turbidity in modern wastewater treatment practices (Teh et al., 2016).

The second stage, physical aggregation, is influenced by the mixing speed. Analysis of variance (ANOVA) showed that while the mixing rate had less impact than the dosage, it still played a significant role in the creation of flocs. At a mixing rate of 140 rpm, sufficient energy is generated by mixing to increase collisions among particles without causing them to break apart. A recent study by Li et al. (2006) showed that for polymeric coagulants, including PAC, it is vital to maintain a moderately high velocity gradient during the aggregation process to prevent larger aggregates from breaking up before separation occurs.

The hydrocyclone completes the separation stage. Separation is based on the mass and stability of the flocs. Flocs at a concentration of 300 mg/L are critical to the centrifugal separation operation (Liu et al., 2024). When water spins in the hydrocyclone (a 15 cm device) under a pressure of 138 kPa, the force of gravity causes the heavier flocs to be pushed outwards. The stability of the flocs ensures that they will not be broken down by the high-pressure flow of water. Instead, they move in a spiral motion downwards and exit through the underflow. In contrast, the light particles that were not adequately removed move along with the inner vortex, which exits through the overflow (Zhang et al., 2024). This verifies that a high removal efficiency in the system is a result of both optimal chemical addition and the physical force of the hydrocyclone.

3.2 Analysis of Particle Size Analysis (PSA) on Floc Dispersion

Although a coagulant dosage of 150 mg/L was used, the removal efficiency was only 67.23%, indicating that many particles remained in the water and did not settle. To understand this, PSA was conducted on the treated water of the suboptimal sample (150 mg/L, 120 rpm).



Figure 8. Particle dispersion in the sample at 150 mg/L PAC dosage and 120 rpm mixing speed

Visual observation in Figure 8 shows that the sample remained cloudy, which was quantitatively confirmed by the PSA results in Table 2. The data reveal a Z-average particle size of approximately 12.5 μm (12,513 nm) with a low polydispersity index (PDI) of 0.119. A PDI value below 0.2 typically indicates a monodisperse and homogeneous distribution (Bhattacharjee, 2016). The diffusion coefficient of $2.69 \times 10^{-11} \text{ m}^2/\text{s}$ further supports this, confirming that the particles were large and moved slowly in the fluid, consistent with the Stokes–Einstein equation (Einstein, 1905).

Generally, particles with a diameter of 12.5 μm are sufficiently heavy to settle. However, the presence of these particles in the samples indicates that the flocs were loose and full of water at a concentration of 150 mg/L. Therefore, the particles were washed away by the water current rather than being separated by centrifugal force (Zhang et al., 2024).

Table 2. Particle Size Analysis (PSA) characteristics of the hydrocyclone treated water at 150 mg/L PAC and 120 rpm

Z Average (nm)	Viscosity (mPa.s)	Temperature (°C)	Count Rate (kcps)
12513.09	0.8869 – 0.8881	25.02 – 25.08	327 - 3689

3.3 Analysis of Zeta Potential and Particle Stability

Figure 8 shows turbid treated water with a coagulant dose of 150 mg/L and a mixing speed of 120 rpm. It proved that the particles did not settle. To determine the stability of the suspended particles, a zeta potential analysis was carried out. The results revealed a measured zeta potential of -23.07 mV (Figure 9). In general, particle stability is governed by the magnitude of the electrostatic charge on the particle surface. Values close to zero, known as the isoelectric point, indicate weaker repulsive forces, allowing particles to agglomerate and settle. In this study, the value of -23.07 mV indicates a condition of partial instability. The surface charge of raw sewage was reduced when the coagulant was added; however, the charge was not completely neutralized. Therefore, a significant repulsive force remained, which prohibited the formation of large and dense flocs. This is also why the 150 mg/L level was less effective, due to incomplete charge neutralization. Ideally, the zeta potential should be reduced to within ± 10 mV to eliminate repulsive forces and maximize separation efficiency (Oyegbile, Ay and Narra, 2016). Moreover, previous studies have reported that highly negative zeta potential values generate strong repulsive forces that maintain particle dispersion (Khani et al., 2025).

Results

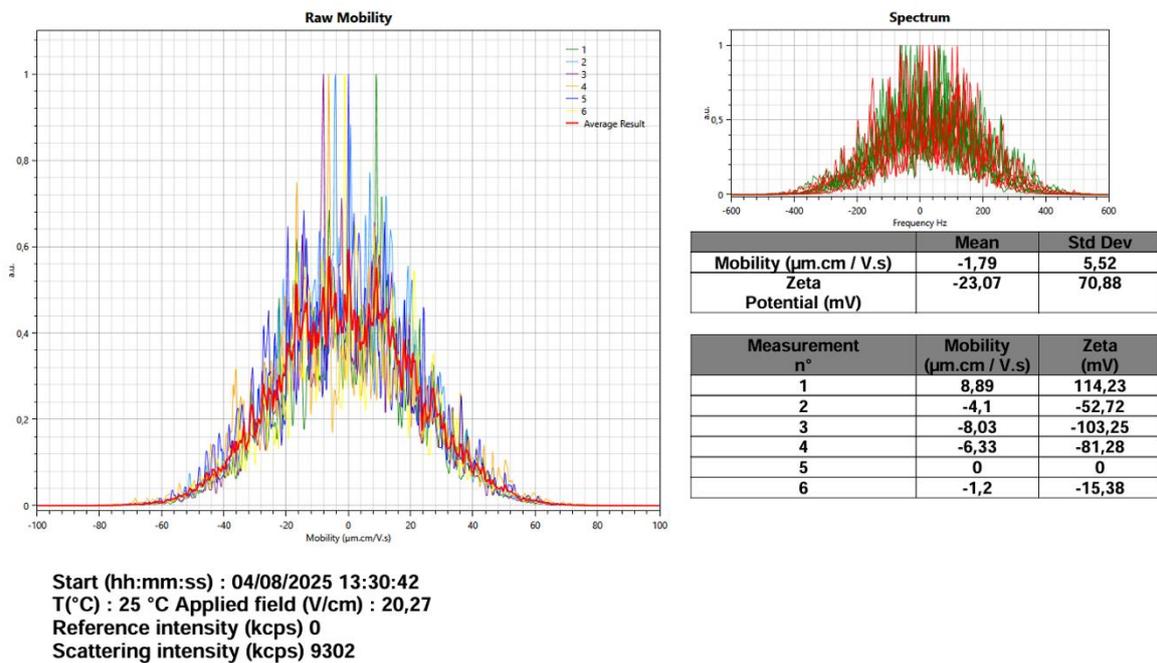


Figure 9. Zeta potential analysis of the treated water at 150 mg/L PAC dosage and 120 rpm mixing speed

3.4 Comparative Performance and Practicality with Existing Technologies

To assess the performance of the PAC-hydrocyclone method, the results were compared with several single and sequencing treatment methods for batik wastewater treatment, as shown in Table 3. The comparison is based not only on the removal percentage but also on the ease of operating the system. This includes factors such as area, time, and budget, which will determine the feasibility of the technology for Indonesian MSMEs.

As shown in the table, the conventional coagulation method using alum (Daud et al., 2023) or bittern salts (Soedjono et al., 2021) is a popular method because of the ease of availability of the materials and their high removal efficiency. However, as explained by Teh et al. (2016), this method produces a large amount of sludge and requires very tight chemical control. Handling large quantities of sludge on a monthly basis in a medium-scale industry incurs hidden costs that cannot be managed by any local operator alone, as they do not have sufficient staff available for manual handling of sludge produced from these levels of production. Hydrocyclone separation produces a cleaner product than manual separation and is therefore a more economical method for this operation.

Table 3. Comparative assessment of removal efficiency and operational feasibility for batik wastewater

Method	TSS removal	Turbidity removal	Operational feasibility	Reference
Single Treatment				
Coagulation-flocculation				
Alum	100%	92.2%	Low cost and high availability, forms much sludge	(Daud et al., 2023)
Bittern salt	-	93.13%	Low cost, requires very careful control	(Soedjono et al., 2021)
Electrocoagulation	93.9%	-	High energy consumption	(Agustina and Yuniarto, 2022)
Chemical method				
TiO ₂ nanoparticles coated	87.5%	-	Requires large tanks	(Sutisna et al., 2017)
ZnO powder	74%	54%		(Khalik et al., 2015)
Electrochemical method				
Stainless steel electrode; alum	95%	56–69%	Requires a constant electricity	(Warjito and Nurrohman, 2016)
Zn electrodes	96.38%	97.61%		(Rahmawati, Suhartana and Gunawan, 2009)
PbO ₂ (anode) and Cu (cathode)	99.7%	-		(Triavia, Widodo and Haris, 2016)
Filtration				
Nanofiltration membrane	100%	99.81%	High cost, filter fouling issues	(Istirokhatun et al., 2021)
Adsorption				
Coal bottom ash	41.6%	75.6%	Requires acid/thermal treatment, produce more hazardous waste	(Jamaludin, 2020)
Sequencing Treatment				
PAC coagulant and filtration	99.5%	-	Better than alum, but still too slow	(Febriasari et al., 2021)
Coagulation-flocculation (Moringa oleifera seeds powder) with constructed wetland	98.11%	-	Requires 5 days retention times and large area	(Rahmadyanti and Febriyanti, 2020)
PAC + hydrocyclone	95.45%	95.24%	Continuous flow, low energy consumption, minimal space requirement	This study

Recent studies have shown that electrochemical and chemical processes are effective wastewater treatment methods (Khalik et al., 2015; Triavia, Widodo, & Haris, 2016; Warjito & Nurrohman, 2016; Sutisna et al., 2017). Certain electrochemical processes can remove up to 99% of contaminants, whereas chemical processes can remove up to 96% of total suspended solids (TSS). Some technologies, such as nanofiltration, are not affordable for many MSMEs and are often subject to membrane fouling, which leads to costly maintenance and repairs. Using PAC alone (Febriasari et al., 2021) is also slow if it relies solely on traditional settling. Additionally, the adsorption of TSS using coal bottom ash (CBA) as a medium is not an effective method (Jamaludin, 2020), as it achieved only a 41.6% removal rate for TSS. This will create safety hazards for workers, as well as generate additional hazardous waste when the ash undergoes acid or heat treatment prior to use; therefore, this requires further testing before it can be used for TSS removal.

Combining Moringa seeds and constructed wetlands achieves high TSS removal efficiency; however, a retention time of five days is required. A combination of extended treatment times and land required for growth makes this option impractical for industries located in urban areas with high population densities (Rahmadyanti & Febriyanti, 2020).

The PAC-hydrocyclone system developed in this study overcame the limitations of earlier systems through the design of a system that was able to remove 95.45% of TSS and 95.24% of turbidity of the wastewater with no large occupied spaces or high energy consumption. It can be continuously flowed through the system with only 60 min of residence time; therefore, it offers a practical compromise for batik producers. This wastewater treatment method has moved away from the traditional method of treating wastewater in slow, static tanks to a compact mechanical method that is more closely related to the economic and physical status of the batik industry.

In this study, a PAC-hydrocyclone system was designed to address these issues. It achieves over 95% removal efficiency of TSS and turbidity with no need for large spaces or high energy inputs. The PAC-hydrocyclone system operates with a continuous flow, using only 60 min of retention time per batch of water. This provides the batik industry with the best option for producing batik. The PAC-hydrocyclone system has a compact design and is of a mechanical nature, offering the batik industry physical and economic characteristics for producing batik.

3.5 Environmental Implication and Future Considerations

Although this treatment method helps remove pollutants from wastewater, it generates a concentrated sludge containing all these pollutants. Studies have shown that the environmental implications of sludge produced at a PAC dosage of 300 mg/L are a major concern. The sludge also contains precipitated aluminum hydroxides and synthetic dyes, which are considered hazardous waste under Indonesian law. For instance, under neutral pH conditions (approximately 7.2), aluminum forms an insoluble precipitate, reducing the leaching of toxic chemicals. Nevertheless, the sludge is classified as hazardous waste because of the presence of dyes. Therefore, proper sludge management represents a major environmental challenge. Recent research has examined the use of sludge in a circular economy, rather than solely viewing it as a waste product. For example, according to a review by Xia et al. (2023), coagulant residuals in sludge could be used as a potential alternative material for the production of low-emission construction materials, such as ceramic bricks.

Because PAC was used as a coagulant in this study, the sludge may contain aluminosilicates; therefore, a detailed chemical and geotechnical characterization of the hydrocyclone underflow is essential in future research. A comprehensive assessment of the sludge composition is the first step in validating its suitability for producing safe bricks locally. The application of this sludge may also extend to the production of pavers or simple concrete for use in manufacturing floor surfaces. Patil et al. 2021 also found that blended concrete containing textile sludges are a viable method of reusing waste streams from industrial processes while maintaining the strength of the final product. This would also enable

medium-sized manufacturing companies to revitalize their manufacturing facility flooring with treated waste and consequently eliminate the costs associated with purchasing new construction materials.

A second realistic possibility involves the wax content in batik wastewater, which has a fairly high energy value; thus, the dry sludge may serve as an alternative fuel source. Chang and Shen (2025) demonstrated that sludge produced from textile wastewater processes can be transformed into solid recovered fuel (SRF) with sufficient calorific value for use in an industrial boiler. This results in a closed-loop system in which the waste generated from processing batik wastewater provides energy to run the heat-intensive portions of the batik-making process, and the energy recovered may keep the factory's electricity expenses low while reducing reliance on external sources of fuel.

In the future, complete water recycling will be possible with further improvements to the system. Hydrocyclones effectively remove suspended solids; however, an additional simple polishing step will help eliminate any remaining colors or odors from the recycled water. The use of low-cost filters made from locally available materials (e.g., coconut shells and/or fruit peels) is a viable and feasible approach. Additionally, Afroze and Sen (2024) demonstrated that these agricultural solid wastes are efficient at adsorbing dyes after primary treatment. Therefore, including this additional filtration step would support industries that want to reuse treated water for the next batik production cycle and can save considerable amounts of water and money.

A basic sensor system could be added to the treatment process to simplify operations for local workers. Simple sensors that are connected to a mobile phone can provide more accurate real-time data on water quality and decrease the uncertainty of treatment efficiency. While this increases efficiency, as indicated by Lakshmikantha et al. (2021), it can also reduce errors made by people to stay compliant with environmental regulations. Consequently, the treated effluent will meet or exceed government standards prior to being released into the local river and protect the environment while allowing the business to operate efficiently.

4. Conclusions

The combination of PAC coagulation and hydrocyclone separation is a feasible and effective method for pretreating batik wastewater. At a coagulant dosage of 300 mg/L and a mixing speed of 140 rpm, the maximum removal efficiencies of total suspended solids (TSS) and turbidity (95.45% and 95.24%, respectively) were observed. From the statistical analysis performed, it was determined that the coagulant dosage was the most significant factor determining treatment performance, greater than the mixing speed.

In addition, chemical stabilization was found to be critical for the success of the treatment process. Zeta potential analysis showed that the optimum dosage decreased the electrostatic repulsive forces and raised the potential to levels greater than -25 mV, which allowed for the formation of dense flocs that could be efficiently separated by centrifugal separation. Conversely, at sub-optimal dosages, stable loose aggregates were created that were not efficiently separated using a hydrocyclone.

This study provides evidence that hydrocyclones are an efficient method for quickly separating solids from liquid waste generated by MSMEs; however, because the focus was limited to assessing physical separation, future studies should include the extraction of dissolved organic pollutants and color from wastewater to evaluate whether they can meet discharge regulations for direct discharge. It is also recommended that future researchers develop a detailed characterization of the sludge produced by hydraulic cyclones to determine its ability to be safely disposed of or used for other purposes in a circular economy.

Acknowledgement

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Ethics Statement

This study did not involve human participants, animals, or any personally identifiable data; therefore, formal ethical approval was not required. Wastewater samples were collected from an industrial drainage channel with permission from the facility owner/management and were handled strictly for research purposes. All laboratory activities were conducted in accordance with standard occupational health and safety procedures. Residual sludge and treated effluents generated during the experiments were managed and disposed of in accordance with applicable local/environmental laboratory waste handling practices.

CRedit Author Statement

Firra Rosariawari: Conceived and Designed Analysis, Performed Analysis, Wrote Paper. **Aussie Amalia:** Conceived and Designed Analysis, Contributed and Analysis Tools, Performed Analysis. **R Mohammad Alghaf Dienullah:** Performed Analysis, Wrote Paper. **Fajar Fauzi Shufianto:** Collected Data, Contributed and Analysis Tools, Wrote Paper. **Fauzul Rizqa:** Performed Analysis, Wrote Paper.

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