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Optimizing Coagulant-Flocculant Composition to Reduce Dissolved Zinc in Electroplating Effluent

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Electroplating liquid waste creates toxic metal-organic complexes, posing a considerable environmental hazard. The primary problem is determining the most efficient and ecologically beneficial approach for processing this waste. One promising approach is the coagulant-flocculant procedure. This study focused on establishing the optimum combination of coagulant and flocculant to decrease Zn heavy metal liquid waste. The research involved experimenting with various compositions of pH, PAC (Poly Aluminium Chloride), and anionic polymers. The jar-test equipment was applied to analyze changes in Total Dissolved Solid (TDS), Zn levels, and turbidity. The findings revealed that the optimal conditions were obtained at pH 8 with 40 ppm coagulant and 0.1 ppm flocculant. TDS increased by 11.05% (from 1262 ppm to 1401 ppm), whereas turbidity and Zn levels fell by 98.17% (from 54 to 1 NTU) and 98.38% (from 9.8 ppm to 0.16 ppm), respectively. These results underline the suitability of this composition for effectively treating increasing volumes of electroplating waste.

Keywords: coagulant, electroplating, flocculant, Zn liquid waste.

Introduction

In the near future, the increasing product in industrial activity will bring about considerable issues linked to solid and liquid waste creation. One of the fastest-growing industrial sectors is electroplating, especially in industrial zones. Electroplating, which involves applying a thin layer of metal onto another metal through electrodeposition, results in the creation of hazardous wastewater containing high concentrations of metal ions including dissolved copper (Cu), nickel (Ni), chromium (Cr), lead (Pb), and dissolved zinc (Zn). The direct discharge of these metal ions into the environment gravely harms living beings' well-being. Extensive research has been undertaken on various techniques of processing waste, such as coagulant-flocculant, ion exchange, membrane filtration, and adsorption (Li et al., 2023; Montaño-Medina et al., 2023; Thiripelu et al., 2024; Zhang et al., 2024). However, not all traditional methods are suggested owing to economic considerations and inefficiency.

The coagulant-flocculant approach is a standard method that is extensively used to remove inorganic or organic suspensions such as dissolved hazardous metals and oily wastes (Skotta et al., 2023; C. Zhao et al., 2021). Coagulation entails the inclusion of coagulants that neutralize the negative charges on particles and dissolved metal ions like Zn. This neutralization destabilizes the particles, allowing them to combine and form larger aggregates. Following coagulation, flocculation occurs, in which bigger flocs are formed as a result of the destabilized particles colliding due to moderate mixing. These flocs can then be removed through sedimentation or filtration (Abujazar et al., 2022; Pillai and Thombre, 2024). The effectiveness of separating suspended particles (colloids) from water has been accomplished by adding different materials such as chitosan, alum, ferric chloride, and polyelectrolytes (Renault et al., 2009). Factors influencing coagulation-flocculation include pH, type of wastewater, dosage, and coagulant-flocculant type (Benalia et al., 2024; Haddaji et al., 2022). Wang et al. (2021) utilized a genetic algorithm to determine the coagulant-flocculant composition in the Cu content reduction process such that it could reduce expenses by up to 10% and boost performance by up to 27%. On the other hand, Amuda et al. (2006) discovered the impact of several pH changes on the effectiveness of the contaminant removal procedure in the beverage industry.

According to such concerns, studies on coagulant-flocculant unsuitable solution pH conditions and dose optimization are required. PAC (Poly Aluminium Chloride) was employed as a coagulant in this research, whereas anionic polymer was used as a flocculant. The inquiry will focus on changes in wastewater quality from three measures, i.e., TDS (Total Dissolved Solid), turbidity, and dissolved Zn concentration. The project intends to find the ideal settings for pH, PAC dosage, and anionic polymer dosage in improving wastewater quality on a laboratory scale utilizing the jar-test technique. This technique will eventually be utilized as a reference in building ideas for electroplating waste management on an industrial scale.

Methods

In order to identify the appropriate dose of coagulant and flocculant at ideal pH values, research was done in three optimization stages: pH, coagulant, and flocculant (see *Fig. 1*). Various water quality metrics such as TDS, turbidity, and dissolved zinc level were assessed throughout each optimization step. The materials utilized in the study comprised PAC as a coagulant, an anionic polymer as a flocculant, caustic soda for pH adjustment, demineralized water to dissolve the coagulant and flocculant, and electroplating wastewater as the research sample. The sample of wastewater is sourced from the electroplating industry (PT. X) in Bekasi City, Indonesia, highlighting the need for effective management of industrial discharges to ensure environmental safety. The wastewater sampling followed the SNI 8990-2021 standard, with the electroplating waste samples above Indonesia's water quality requirements threshold (Table 1). Apera PC 8500 was utilized for pH and TDS measurements, whereas a turbidity meter SgZ-200BS was used for turbidity measurements. A spectrophotometer (PG Instruments T60 UV-VIS) was used to determine the dissolved zinc level using the Zincon method at 620 nm. Following the procedure outlined by Säbel et al. (2010), proper sample preparation, reagent addition, and absorbance measurement were conducted to obtain accurate zinc concentrations.

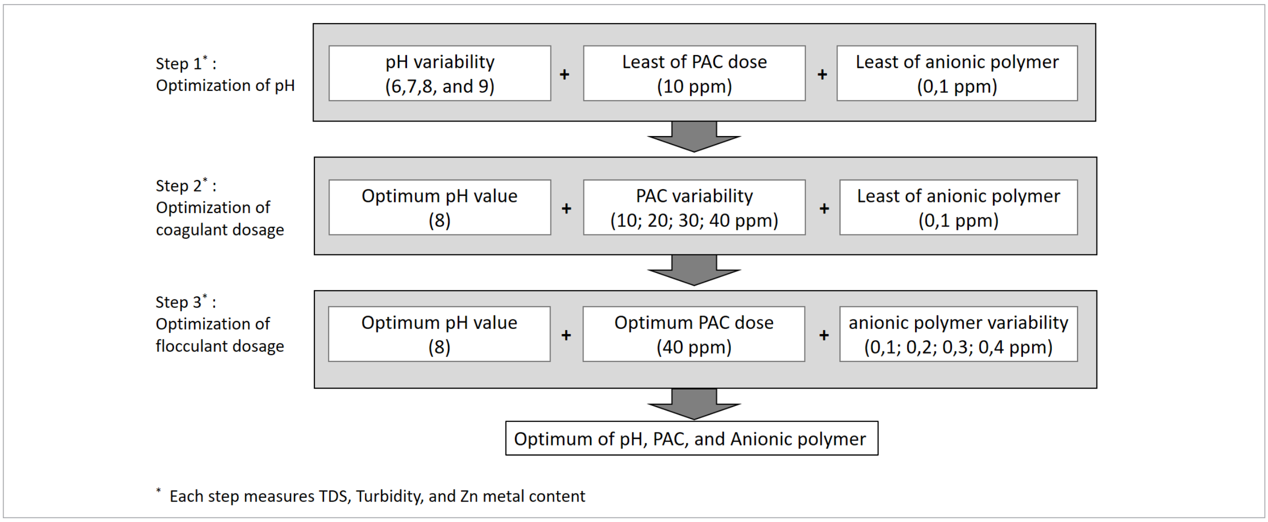
Table 1. *Sample of wastewater compared to Indonesian's water quality standard regarding four parameters*

Parameter	Sample of electroplating's wastewater*	Indonesian water quality standard**
pH	5.0 + 0.3	6–9
TDS (ppm)	1262 + 170	2000
Turbidity (NTU)	54.1 + 1.2	5–25
Zn metal content (ppm)	9.8 + 0.9	5

* In average value and standard deviation with n=3.

** Quality standard of domestic water according to Republic Indonesia Government (PERMEN LHK RI No. 6, 2021).

Fig. 1. *Research procedure for pH, PAC, and anionic polymer optimization*



The jar test technique applied to identify the optimum dosage of coagulant-flocculant at the best pH value. In the first step (pH optimization), the pH changes employed in this therapy are 6, 7, 8, and 9. All pH fluctuations are evaluated with a dosage of 10 ppm PAC and 0.1 ppm anionic polymer. In the second step (PAC optimization), pH with the best results will then be retested with PAC dosage changes of 10 ppm, 20 ppm, 30 ppm, and 40 ppm, as well as 0.1 ppm anionic polymer and the last stage is the optimization of anionic polymer (flocculant) dose. After the optimal pH and coagulant dosage findings are determined, testing is continued with anionic polymer dose changes of 0.1 ppm, 0.2 ppm, 0.3 ppm, and 0.4 ppm. The solution mixture at each stage was stirred using a flocculator (Scientifica FP4) with a pH adjustment procedure using caustic soda until the desired pH was obtained, then coagulant was added according to the treatment dose and fast rotation (200 rpm) for 5 minutes), then flocculant was added, and slow rotation (100 rpm for 10 minutes) was carried out. Then, the solution was left for 15 minutes to test water quality parameters (specifically, TDS, turbidity, and dissolved Zn concentration) at each step.

Results and Discussion

pH optimization

In addition to being an indicator of a solution's acidity or alkalinity, pH also considerably influences the wastewater treatment process. Various pH levels influence the quality parameter values of wastewater samples (*Table 2*). The findings of pH fluctuations on TDS reveal that boosting the amount of caustic soda can raise TDS because caustic soda contains a highly alkaline component. When added to water, sodium (Na) and hydroxide (OH) ions will dissolve such that they can increase TDS levels (Trinuruk et al., 2021). Nurul Hanira et al. (2017) showed caustic soda usage to improve pH, followed by an increase in TDS of 77.62 ppm (from 322.22 ppm to 399.84 ppm). The pH value on turbidity illustrates that an increase in pH can affect the decrease in turbidity. This is because at low pH (pH < 6), suspended particles tend to be more stable and prone to aggregate, increasing turbidity. Meanwhile, at high pH (pH> 6–9) can make coagulants and flocculants perform ideally so that they can more efficiently agglomerate particles and minimize turbidity. The consequences of pH fluctuations on Zn levels demonstrate a reduction in Zn levels. This happens because at a higher pH the Zn^{2+} ion combine with the OH^- ion from caustic soda to generate zinc hydroxide ($Zn(OH)_2$). At a given pH level, it will yield optimal $Zn(OH)_2$ precipitation. Theoretically, pH 9.5 is the optimal pH that can precipitate $Zn(OH)_2$ up to 0.1–0.2 ppm. However, in this study, the pH value employed was 6 to 9. In addition, the findings of the decline in Zn levels in the pH fluctuations of this study were obtained at pH 8 and 9, which might drop to 0.21 ppm. This is because practically all Zn metal has precipitated.

Table 2. *Water quality parameters regarding pH variabilities*

pH	PAC (ppm)	Anionic polymer (ppm)	Water quality parameters		
			TDS (ppm) ± sd.	Turbidity (NTU) ± sd.	Zn content (ppm) ± sd.
6	10	0.1	1350 ± 43.59	4.30 ± 0.70	0.47 ± 0.09
7			1356 ± 33.86	1.37 ± 0.21	0.43 ± 0.08
8			1383 ± 55.65	1.20 ± 0.10	0.28 ± 0.06
9			1390 ± 60.25	1.20 ± 0.10	0.27 ± 0.07

Notes: sd. refers to standard deviation

PAC optimization

PAC has a substantial influence on the quality of electroplating wastewater. The findings of employing 0.4 ppm PAC with pH 8 and 0.1 ppm anionic polymer indicated the slightest drop in turbidity (1.0 NTU) and a decrease in dissolved Zn levels of up to 0.16 ppm while it is inversely proportional to TDS of 1404 ppm (*Table 3*). The impact of PAC modifications on TDS demonstrated an increase in TDS levels. The increase occurs because PAC includes aluminum and chloride when applied in more significant concentrations, can cause more ions to dissolve in water (Riveros, 2018). Each increase in PAC dosage elevates the concentration of these ions, so that TDS rises. In addition, high coagulant dosage might create less effective coagulation or deflocculating when previously coagulated particles are released back into the solution, which can increase the number of dissolved chemicals (Widiyanti, 2019).

Table 3. *Water quality parameters regarding coagulant variabilities*

pH	PAC (ppm)	Anionic polymer (ppm)	Water quality parameters		
			TDS (ppm) ± sd.	Turbidity (NTU) ± sd.	Zn content (ppm) ± sd.
8	10	0.1	1353 ± 42.04	1.20 ± 0.10	0.28 ± 0.06
	20		1380 ± 55.68	1.17 ± 0.15	0.19 ± 0.02
	30		1387 ± 57.46	1.17 ± 0.15	0.47 ± 0.07
	40		1404 ± 70.61	1.00 ± 0.20	0.16 ± 0.07

Notes: sd. refers to standard deviation

The findings of the PAC turbidity variation demonstrate a decrease in turbidity seen at each dose, namely 10 ppm, 20 ppm, 30 ppm, and 40 ppm at pH 8 and the addition of 0.1 ppm flocculant. This is because greater amounts of PAC (between 10 and 40 ppm) neutralize more suspended particles in the water, which makes the water cleaner due to the PAC coagulant's positive charge. The water gets clearer because the suspended particles in the water that generate turbidity will react with the positive charge of the PAC coagulant which then creates flocs that may settle (Zhao et al., 2012). The most effective doses for coagulating and precipitating zinc to lower its concentration are 10 ppm and 20 ppm. However, at a dosage of 30 ppm, there was less efficient coagulation or deflocculating, which increased Zn levels because the coagulated particles were broken down and Zn was released back into the water. Coagulation stability increased at a dose of 40 ppm, reducing Zn levels. Thus, the optimal Zn metal reduction result in coagulant fluctuations of 40 ppm was reached.

Anionic optimization

Using anionic polymers as flocculants at a fixed pH of 8 and PAC value of 40 ppm has demonstrated optimum performance at a dosage of 0.1 ppm (see *Table 4*). At this level, turbidity can be reduced to 1.00 NTU, and the reduction in Zn levels reaches 0.16 ppm. Additionally, it was noticed that the rise in TDS values at each dose was 0.1 ppm, 0.2 ppm, 0.3 ppm, and 0.4 ppm at pH 8 with the addition of 40 ppm coagulant. The significant rise in TDS is attributable to the excessive use of flocculants, which may result in deflocculating and the reformation of suspended particles (Amarjargal and Taşdemir, 2023).

Table 4. *Water quality parameters regarding flocculant variabilities*

pH	PAC (ppm)	Anionic polymer (ppm)	Water quality parameters		
			TDS (ppm) ± sd.	Turbidity (NTU) ± sd.	Zn content (ppm) ± sd.
8	40	0.1	1401 ± 67.55	1.00 ± 0.02	0.16 ± 0.07
		0.2	1405 ± 70.04	1.03 ± 0.21	0.31 ± 0.07
		0.3	1408 ± 72.17	1.03 ± 0.21	0.20 ± 0.06
		0.4	1409 ± 72.29	1.10 ± 0.26	0.18 ± 0.05

Notes: sd. refers to standard deviation

The findings of the variation of anionic polymers on turbidity describe the effects of lowering and raising turbidity. A dosage of 0.1 ppm is adequate to decrease turbidity optimally. A dosage of 0.2 ppm rises and 0.3 ppm has the same value as a dose of 0.2 ppm. Therefore, there is no change in turbidity. At a level of 0.4 ppm, there is a rise again. Turbidity increases because of adverse effects such as less efficient coagulation or deflocculating. These results show an optimal flocculant dosage; greater doses do not necessarily result in decreased turbidity.

The study results demonstrate the impact of anionic polymers on dissolved Zn levels, revealing the potential to decrease and increase heavy metal Zn. A dose of 0.2 ppm increased Zn concentration due to ineffective flocculation, causing Zn to remain suspended in water. Conversely, 0.1 ppm, 0.3 ppm, and 0.4 ppm effectively formed stable flocs, leading to Zn precipitation or removal. The experiment identified the optimal flocculant dose as 0.1 ppm.

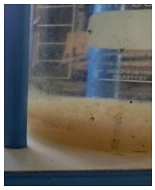
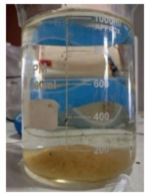
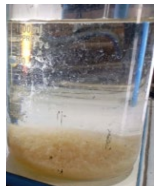
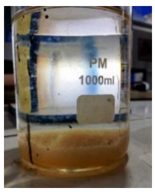
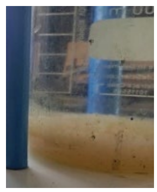
Potential of coagulant-flocculant approach in electroplating's wastewater management

The electroplating industry is developing rapidly along with the automotive industry. The heavy metal waste from the electroplating industry is classified as Toxic and Hazardous Materials, such as Cu, Cr, Zn, Ni, Fe, etc. (Ayub et al., 2020; Fang et al., 2012). Globally, more than 11 million tons of zinc are produced yearly, with the electroplating sector using almost half of it for galvanizing steel to prevent corrosion. An estimated 2–20% of the metals and chemicals employed in the process wash away and wind up in the wastewater that is produced (Kamar et al., 2022). Industry must process this waste before it is released into the environment or reused. Various methods reduce dissolved Zn levels, such as coagulation and flocculation, chemical precipitation, ion exchange, membrane filtration, adsorption, electrochemical treatment, and advanced oxidation process (Rajoria et al., 2022). The coagulant-flocculant method is an alternative because of the cost and simplicity of the process, but it has good performance (Iwuozor, 2019). Current developments seek the right coagulant and flocculant ingredients and composition to increase efficiency and effectiveness. Research on PAC as a coagulant and anionic polymer as a flocculant has different performances even under ideal pH conditions (*Table 5*). On visual observation of the various variations used, at pH eight, it was found that perfect clumping occurred at a PAC dose of 40 ppm and an anionic polymer dose of 0.1 ppm.

The results for four key water quality parameters (i.e., pH, zinc metal content, turbidity, and TDS) were analyzed for two types of water samples: wastewater and treated water, which used an optimized coagulant-flocculant dosage (see *Fig. 2*). The optimized treatment successfully raised the pH of the wastewater to within the acceptable range for environmental discharge or potential reuse, effectively correcting its acidity. The treatment significantly reduced the zinc concentration, substantially below the regulatory threshold. This indicates excellent removal efficiency for heavy metals, likely achieved through adsorption and sedimentation during flocculation. The turbidity levels were severely lowered, going beyond acceptable limits, showing the coagulant-flocculant's success in removing floating solids, typically the most noticeable polluters in wastewater. However, the levels of TDS increased slightly after treatment, which may be attributed to the dissolution of coagulant salts or chemical residues. Despite this increase, the TDS values remain within acceptable limits, suggesting that the coagulation-flocculation process is not specifically aimed at removing dissolved ions. While the treatment is highly effective in removing particulate metals and improving water clarity, it is not designed to address dissolved substances.

Decreasing dissolved Zn level by 98.71% and turbidity by 98.38%. Despite rising TDS and pH levels due to chemical-physical interactions, these levels stay below permissible ranges according to water quality regulations. In comparison, the combined electrochemical and ozonation technique provides a 99.97% decrease in Zn levels (Orescanin et al., 2013). The electrochemical ozone is a potent oxidizing agent that converts Zn^{2+} into less soluble forms (e.g., $Zn(OH)_2$), enhancing its removal efficacy and eliciting localized pH changes, promoting the precipitation of Zn as $Zn(OH)_2$ (García-Orozco et al., 2016; Liu et al., 2025). Therefore, this process eliminates Zn more rapidly than the coagulation-flocculation procedure, which needs settling time for flocs to form and separate. However, the difference between both techniques in Zn reduction is insignificant. If energy and infrastructure costs are not a significant concern, the electrochemical-ozonation method is a more sustainable and efficient option. Nonetheless, the coagulant-flocculant approach remains a practical choice for large-scale operations with budget constraints (López-Maldonado et al., 2014; Wei et al., 2018).

Table 5. *Visual interpretation of coagulant-flocculant process in each treatment*

pH variability*		Coagulant variability**		Flocculant variability***	
Figure	Visual interpretation	Figure	Visual interpretation	Figure	Visual interpretation
	pH = 6 The wastewater appears turbid and contains numerous floating flocs.		PAC = 10 ppm The wastewater appears limpid; bit-floating flocs appear.		Anionic polymer = 0.1 ppm The wastewater appears limpid; flocs have clumped.
	pH = 7 The wastewater appears a bit clearer; the flocs are seen to have clumped together; some floating flocs appear.		PAC = 20 ppm The wastewater appears limpid; bit floating flocs appear.		Anionic polymer = 0.2 ppm The wastewater appears limpid; flocs have clumped.
	pH = 8 The wastewater appears limpid; flocs have clumped.		PAC = 30 ppm The wastewater appears limpid; bit floating flocs appears		Anionic polymer = 0.3 ppm The wastewater appears limpid; flocs have clumped
	pH = 9 The wastewater appears limpid; flocs have clumped.		PAC = 40 ppm The wastewater appears limpid; flocs have clumped		Anionic polymer = 0.4 ppm The wastewater appears limpid; flocs have clumped.

Notes: * treatment utilizing varied pH values, whereas the other values were selected as the least (PAC = 10 ppm and anionic polymer = 0.1 ppm).
** treatment utilizing varied PAC values, whereas the other values were selected as optimum pH (8) and the least anionic polymer (0.1 ppm).
*** treatment utilizing varied anionic polymer values, whereas the other values were selected as optimum pH (8) and PAC (40 ppm).

Conclusions

The effective application of conventional flocculants and coagulants in treating electroplating wastewater on a laboratory scale indicates their potential for industrial implementation. Using appropriate coagulant and flocculant doses and pH level modifications, the turbidity and dissolved zinc content decrease until below the acceptable disposal standards. Furthermore, the optimum treatment, with a pH of 8, a 0.4 ppm PAC dosage, and a 0.1 ppm anionic polymer dose, resulted in a round 98.17% decline in turbidity (from 54 to 1 NTU) and a 98.38% reduction in dissolved zinc content (from 9.8 to 0.16 ppm). These results aid in the development of large-scale waste management systems for electroplating. However, consistency in performance is necessary for scaling up the technique.

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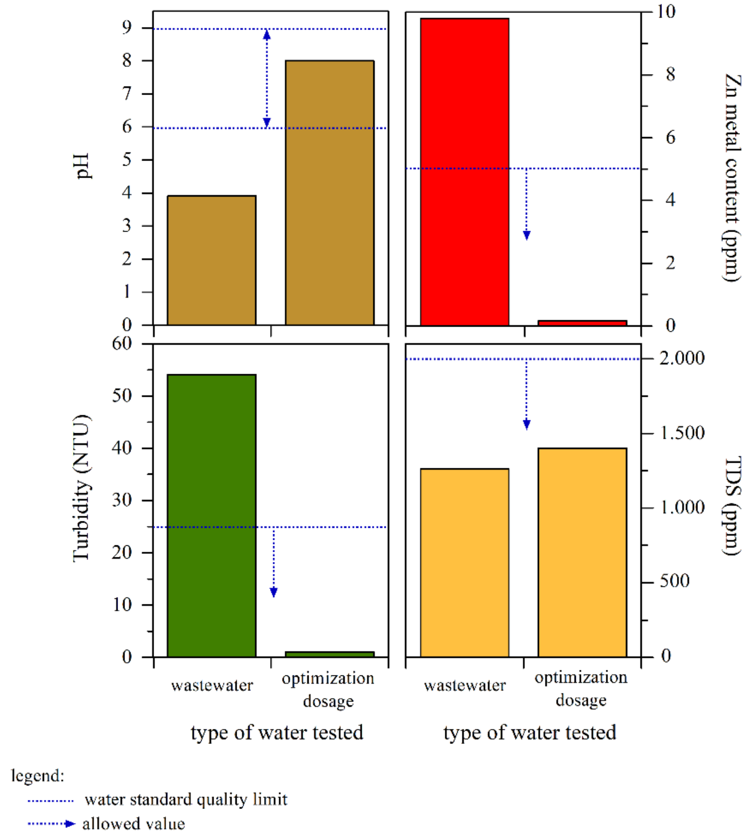
Fig. 2. *Water quality values of wastewater's sample and optimization dosage of coagulant-flocculant*



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