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Analysis and operational improvement of a dissolved air flotation device treating wastewater from the production of electrical equipment

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ABSTRACT

The industrial sector faces increasing pressure to adopt sustainable practices, driven by the significant environmental impacts of wastewater discharge into aquatic ecosystems. This study evaluated the efficacy of three chemical coagulants in reducing turbidity and solids concentration in wastewater generated by an electrical equipment manufacturing facility. The research also explored the synergistic effects of coagulant application on enhancing the performance of the dissolved air flotation (DAF) system integrated into the industry's wastewater treatment plant (WWTP). The experimental methodology involved preliminary Jar test assays to determine optimal coagulant dosages for maximizing turbidity reduction without adjusting the wastewater's initial pH. Subsequently, on-site trials were conducted, introducing the predetermined coagulant dosages before DAF treatment. In the preliminary stage, the coagulants tested were aluminum sulfate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), and aluminum polychloride (PAC). The dosages that provided the highest turbidity removal efficiencies were 4, 35, and 40 mg.L^{-1} for the PAC, $FeCl_3$, and $Al_2(SO_4)_3$, respectively. Only the PAC and $Al_2(SO_4)_3$ were tested in the on-site tests. 40 mg.L^{-1} of $Al_2(SO_4)_3$ showed greater efficiency in removing total solids (TS) and total suspended solids (TSS). Turbidity removal was more effective using PAC at 4 mg.L^{-1} dosage. A comparative cost analysis revealed that PAC is a more economical coagulant than $Al_2(SO_4)_3$ for operating the DAF system, with a 40.65% lower cost, making it the optimal choice for the industrial WWTP.

Keywords: Comparative costs, oily effluents, turbidity.

Introduction

Industrialization is a main contributing factor to increasing soil and water pollution worldwide. In general, industrial activities demand high-quality water and, in turn, produce large volumes of contaminated wastewater. The discharge of this waste into receiving water bodies is of great concern from an environmental and health point of view (Meyer et al. 2019; Iloms et al. 2020).

In the production of household electrical equipment, sanding metal parts is a critical step, typically performed using an orbital sander that employs rapid circular motions. A significant volume of water is required to flow between the sandpaper and the metal surface to prevent overheating. This process generates an effluent composed of water, aluminum, and silica (from the sandpaper), which undergoes simple filtration through the non-woven fabric to remove larger particles, allowing the water to be reused in the polishing process. Such water reuse is a key practice for Cleaner Production (Van Berkel, 2007). Additionally, maintenance and repair activities in the facility introduce oil residues, solvents, lubricants, paints, and greases into the effluent, giving it an oily characteristic. The low solubility of oils and greases poses challenges for biological treatment and, if discharged into natural water bodies, can form an insoluble film at the air-liquid interface, blocking sunlight and impairing gas exchange, thereby harming aquatic ecosystems (Cristóvão et al., 2016).

The dissolved air flotation (DAF) process operates on the principle of suspending particulate matter through the injection of micro-bubbles at the bottom of the unit. These micro-bubbles carry the waste to the surface, where the resulting suspension (flotation residue) can be removed using conventional physical methods such as scraping or suction (Di Bernardo & Dantas, 2005). As a physical separation technique, flotation is particularly effective for clarifying effluents with high oil and grease concentrations (Di Bernardo & Dantas, 2005). Due to this efficiency, DAF was selected as the primary treatment unit for the industry under study, ensuring the effective removal of contaminants before further processing.

Following the dissolved air flotation (DAF) process, the treated effluent is combined with domestic sewage from the industry's canteens, toilets, and cleaning activities and then directed to an aerobic biological treatment unit utilizing activated sludge. Tamburus et al. (2020) evaluated the performance of the aerated tanks in this system by analyzing the biological flocs' microfauna, structure, and sedimentability. Their findings revealed low microbial diversity (indicating poor sludge quality) and inadequate sedimentability (Tamburus et al., 2020). These issues can likely be attributed to the high turbidity of the effluent entering the activated sludge system from the DAF unit.

The addition of coagulants and flocculants 222in DAF processes is known to enhance separation efficiency by increasing bubble-particle collision rates, accelerating flotation kinetics, and improving air utilization (Han, Kim & Kim, 2007; Wang et al., 2021). This practice is widely adopted in industrial wastewater treatment plants (Lee, Robinson & Chong, 2014). Coagulation involves a chemical reaction between the coagulant and water, forming hydrolyzed species, followed by a physical stage where these species interact with impurities in the water (Di Bernardo & Dantas, 2005).

The selection of an appropriate coagulant and its optimal dosage depends on the effluent's characteristics and economic feasibility, typically determined through treatability tests. Commonly used chemical coagulants include aluminum and iron salts, favored for their cost-effectiveness and coagulation efficiency (Lédo, Lima & Paulo, 2010; Vaz et al., 2010). Widely utilized options include aluminum sulfate, ferrous sulfate, ferric sulfate, ferric chloride, chlorinated ferrous sulfate, sodium aluminate, and polyaluminum chloride (PAC - $[Al_2(OH)_nCl_{6-n}]_m$) (Manda et al., 2016).

The Jar test is a widely used method for determining the optimal dosage and type of coagulant and evaluating the hydrodynamic mixing conditions essential for effective coagulation. Although the mixing conditions and floc sizes generated in Jar tests differ from those in pilot-scale or full-scale tests, Saxena & Brighu (2020) note that these differences are minimal and do not significantly affect wastewater quality, making the Jar test a reliable tool for preliminary assessments.

In this study, the efficiency of three chemical coagulants - aluminum sulfate ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), and polyaluminum chloride (PAC) - was investigated for reducing turbidity and solids concentration in wastewater from an electrical equipment manufacturing industry. The research also explored how coagulant use could enhance the performance of the existing dissolved air flotation (DAF) unit at the industry's wastewater treatment plant (WWTP). Finally, an economic evaluation of the most effective coagulants identified during on-site testing was conducted to support decision-making for optimizing WWTP's operational processes.

Material and Methods

Characteristics of the wastewater and the production process

The effluent generated from the polishing and sanding metal parts is combined with waste oils, solvents, lubricants, paints, and greases from equipment maintenance and repair activities and then directed to the industrial WWTP. Upon arrival at the DAF system, the raw effluent exhibited the following characteristics: pH of 8.15, turbidity of 118 ± 6.7 NTU, temperature of 26°C, total solids (TS) of 1852 $mg \cdot L^{-1}$, total suspended solids (TSS) of 733 $mg \cdot L^{-1}$, and total dissolved solids (TDS) of 786 $mg \cdot L^{-1}$.

The wastewater flow rate ranges between 15 and 24 m^3 per week. The industrial WWTP comprises preliminary, primary, and secondary treatment stages. Preliminary treatment involves screening with parallel metal bars spaced 2" apart to retain coarse suspended solids and floating materials. The screened wastewater is then conveyed to two equalization tanks. A helical pumping unit (Geremia, WHT 32) transports the oily wastewater to the DAF system.

Flotation is characterized by combining a saturation chamber and a flotation tank. Under these conditions, the total pressurization method is used, where the entire inflow is pressurized.

According to Lédo, Lima & Paulo (2010), total pressurization is recommended when the liquid to be clarified contains suspended solids. This pressurization aims to reduce the specific mass of the floc, allowing the suspended material to immerse in the flotation tank (Di Bernardo & Dantas, 2005). At the entrance to the activated sludge system, domestic sewage is added from the industry's canteens, toilets, and cleaning activities. After the decantation stage, the final effluent is discharged into a class 2 receiving body, following the guidelines of CONAMA Resolution 357 of March 17th, 2005 (Brasil, 2005).

Experimental protocol

This study was conducted in two stages. The treatability tests (preliminary stage) were carried out using jar test equipment (SP Labor) and aimed to define the coagulant dosages that would allow the greatest reduction in wastewater turbidity. Table 1 shows the characteristics of the coagulants and the dosages tested in the preliminary stage.

Table 1. Characteristics of the chemical coagulants and dosages tested in the treatability trials. Source: Prado et al. (2023).

Coagulant	**Brand**	**Active content**	**Density**	**Dosages tested in the preliminary stage**
		(%)	**(g cm^{-3})**	**(mg.L^{-1})**
$Al_2(SO_4)_3$	Quimipool Decânter	-	-	30, 40, and 50
$FeCl_3$	Projesan Saneamento Ambiental	38.25	1.4	15, 25, and 30
PAC	Projesan Saneamento Ambiental	16.27	1.358	4, 5, and 6

Each dosage was tested in triplicate, and their values were based on the results observed by Ariano (2009), Lédo et al. (2010), and Vaz et al. (2010), who evaluated the removal of turbidity from different wastewaters by coagulation/flocculation and flotation processes using the coagulants PAC, aluminum sulfate, and ferric chloride, respectively. The Jar test operation followed the sequential steps of rapid mixing under agitation of 750 rpm (duration 15 seconds) and sedimentation (30 minutes). The turbidity values of the raw wastewater and the final effluent (after decanting) were measured to calculate the removal efficiency (%). Statistical analyses (Minitab software) of the initial and final turbidity results and removal efficiencies were carried out to help define the optimum dosages for each coagulant.

After analyzing the performance of the treatability tests, the on-site tests (second stage) were carried out, in which the effects of turbidity removal and solids removal in the DAF unit were assessed. To this end, specific volumes of each coagulant (related to the optimum dosages) were added to the equalization tank of the industrial WWTP. The effluent and coagulant tank was then homogenized, and an initial sample was taken. Next, the dissolved air flotation was activated, and a sample of the final effluent was collected. All the samples were stored in sanitized plastic bottles and submitted to quantify the physico-chemical variables of interest at the Sanitation Laboratory of Universidade Federal do Triângulo Mineiro (UFTM).

Physico-chemical analyses

The following physico-chemical parameters were monitored: pH, temperature, turbidity, total solids (TS), total suspended solids (TSS), and total dissolved solids (TDS). Solids concentrations were determined following APHA (2012). Turbidity and pH were measured using bench-top equipment: MS TECNOPON Instrumentação Científica turbidimeter (model TB 1000) and an mPa - 210 pH meter.

Cost analysis

The economic assessment of coagulant usage is critical for determining the feasibility of adding coagulants to the industrial WWTP's operating routine. This analysis is particularly important when cost-effectiveness and operational efficiency are key decision-making factors. Based on the optimal coagulant dosages identified in the experimental phase, this section presents the cost analysis for incorporating aluminum sulfate and PAC.

Equations 1 and 2 calculated the mass of aluminum sulfate and the volume of PAC required to operate the DAF unit per week, respectively.

$$M = Q \times C \quad \text{Eq.(1)}$$

where: m = mass of aluminum sulphate (kg.week^{-1}) required; Q = flow rate of wastewater arriving at the DAF unit (m³ week^{-1}); C = optimum coagulant concentration (kg m^{-3}).

$Vol = Q \times C$ Eq.(2)

where: Vol = necessary PAC volume (L week^{-1}); Q = flow rate of wastewater arriving at the DAF unit (m^3 week^{-1}); C = optimum coagulant concentration (L m^{-3}).

After determining the mass and volume of coagulants, Equations 3 and 4 were used to calculate the total weekly costs for aluminum sulfate (Total cost 1) and PAC (Total cost 2), respectively.

$Total\ cost_1 = m \times P_{kg}$ Eq.(3)

where: Total cost$_1$ = total cost of aluminum sulfate per week in Brazilian reais (R\$ week^{-1}); m = required mass of coagulant (kg week^{-1}); P_{Kg} = commercial price per kilo of coagulant in Brazilian reais (R\$ kg^{-1}).

$Total\ cost_2 = Vol \times P_{Kg}$ Eq.(4)

where: Total cost$_2$= total cost of PAC per week in Brazilian reais (R\$ week^{-1}); Vol = required volume of coagulant (L week^{-1}); PKG = commercial price per liter of coagulant in Brazilian reais (R\$ L^{-1}).

Results and Discussion

Treatability tests

In the preliminary tests, the raw wastewater had a high initial turbidity, which may be related to the excessive amount of aluminum and silica particles from the grinding process in the polishing machine. All coagulants reduced the turbidity of the raw wastewater (Table 2).

Table 2. Turbidity removal efficiencies achieved in preliminary laboratory tests. Font: Prado et al. (2023).

Coagulant	Dosages (mg.L^{-1})	Final pH	Turbidity removal efficiency (%)
$Al_2(SO_4)_3$	30	8.12 ± 0.08	58.0 ± 12.1
	40	8.06 ± 0.14	72.7 ± 5.8
	50	8.08 ± 0.12	76.4 ± 5.8
$FeCl_3$	15	8.01 ± 0.11	46.2 ± 12.7
	25	7.99 ± 0.10	51.3 ± 8.0
	35	8.05 ± 0.14	72.5 ± 13.8
PAC	4	7.77 ± 0.32	72.7 ± 10.4
	5	7.89 ± 0.28	76.7 ± 6.3
	6	8.07 ± 0.19	35.1 ± 9.3

The best turbidity removal efficiencies for aluminum sulfate were observed for the 40 and 50 mg L^{-1} dosages (Table 2). The Mann-Whitney Rank Sum test indicated a statistical difference (p-value<0.05) when comparing the initial turbidity values for these two dosages. Therefore, the optimum dosage was determined by analyzing the lowest final turbidity rather than the removal efficiency. The lowest final turbidity achieved with the 40 mg L^{-1} dosage was 22 NTU at a pH of 8.04. Considering the 50 mg L^{-1} dosage, the lowest final turbidity was 21 NTU at a pH of 8.21. It can, therefore, be stated that both dosages resulted in a final effluent with equivalent turbidity. For this reason, it was considered more economically advantageous to use the dosage of 40 mg.L^{-1} of aluminum sulfate in the on-site tests.

Vaz et al. (2010) also observed higher removal efficiencies for color (98.1%) and turbidity (98.8%) in coagulation/flocculation tests applied to the treatment of electroplating effluent using 40 mg L^{-1} of aluminum sulfate and a sedimentation time of 20 minutes. In the study carried out by Ferrari, Julio & Julio (2011) for the treatment of public water supply, aluminum sulfate showed two regions with a turbidity removal efficiency of over 60%. The first region was identified as a dosage of 30 mg.L^{-1} and a pH of less than 5, with the adsorption and charge neutralization mechanism predominating due to the low pH (Ferrari, Julio & Julio, 2011). The second region was identified with an average pH of 7.3 and a dosage of 50 mg.L^{-1}, with the sweeping removal mechanism predominating (Ferrari, Julio & Julio, 2011).

In the treatability tests applying PAC, the best removal efficiencies were observed for 4 and 5 mg L^{-1} (Table 2). The T-test indicated no statistical difference between the raw water turbidity values in the tests with dosages of 4 and 5 mg L^{-1}, so the best dosage was based on comparing the maximum turbidity removal efficiencies, which were equivalent for both dosages. The maximum removal efficiency at a 4 mg.L-1 dosage was 84.5% at pH = 8.01. For the 5 mg L^{-1} dosage, the highest efficiency (83.9%) was obtained at pH 8.17. Therefore, the 4 mg L^{-1} dosage was considered the most economically viable and was adopted in the on-site tests.

Due to the small variation in the dosage ranges applied for the three coagulants, PAC (polyaluminum chloride) exhibits an inverse trend compared to the others, reducing turbidity removal efficiency as the dosage increases. However, this decline in efficiency is natural for all coagulants, as demonstrated by jar test experiments and particularly by the work of Asmel et al. (2021). Regarding PAC, other studies have also shown this trend of reduced turbidity removal efficiency with increasing dosage. For instance, Alvim et al. (2022) applied PAC in the 0.5 to 2.0 mg L^{-1} range for dairy effluent, with the best results achieved at a dosage of 0.8 mg L^{-1}. Another study supporting this trend is that of Souza et al. (2016), who applied PAC to textile industry effluent at dosages between 0.2 mg L^{-1} and 0.6 mg L^{-1}, achieving optimal turbidity removal efficiency at dosages between 0.3 mg L^{-1} and 0.4 mg L^{-1}.

Among the three coagulants tested, the greatest instability in final turbidity values was observed in the tests using ferric chloride. The 35 mg.L^{-1} ferric chloride dosage had the highest average turbidity removal efficiency for the effluent under study (Table 2). At a dosage of 35 mg.L^{-1} of ferric chloride, the average pH was 8.05 ± 0.14, with the highest absolute turbidity removal efficiency (86.3%) observed at pH = 8.19 and the lowest efficiency (42.3%) at pH = 7.96. In addition, it was observed that the effluent acquired a yellowish/turquoise color for the three dosages tested, which may be related to the excessive presence of iron (Vaz et al., 2010). In the tests with $Al_2(SO_4)_3$ and PAC, it was observed that the flocs formed smoothly without changing the color of the effluent. Given the above, it was decided to evaluate only aluminum sulfate and PAC use in the on-site tests.

On-site tests

This stage was used to analyze the effects of the prior edition of the coagulants PAC and aluminum sulfate on turbidity and solids removal (TS and TSS) in the effluent going through the flotation process. To assess possible improvements in efficiency due to the addition of coagulants, the flotator was also operated without the prior addition of coagulants. This test illustrates how the current primary treatment of the industrial WWTP is carried out. Figure 1 presents the main results regarding removal efficiency (%).

Concerning solids removal, it was noted that the FAD system operated without prior addition of coagulants achieved TS and TSS removal efficiencies of 34.13% and 64.53 % (Figure 1). TSS removal efficiencies of more than 50% were already expected for DAF operation without adding coagulants or flocculants. This is due to the good performance of flocculation units in removing this compound, as observed by Coutinho (2007). This author achieved 98% efficiency in removing the TSS load from samples of the Ressaca and Sarandi streams, tributaries of the Pampulha Reservoir (Belo Horizonte-MG), via the DAF process.

Figure 1 shows that adding the two coagulants increased the removal of solids after flotation, with aluminum sulfate providing the most efficient TS (95.6%) and TSS (83.3%) removals. According to Shahbazi, Rezai & Koleini (2010), particle aggregation increases the probability of bubble-particle collision in the flotator, increasing the flotation kinetics and the efficiency of using airflow.

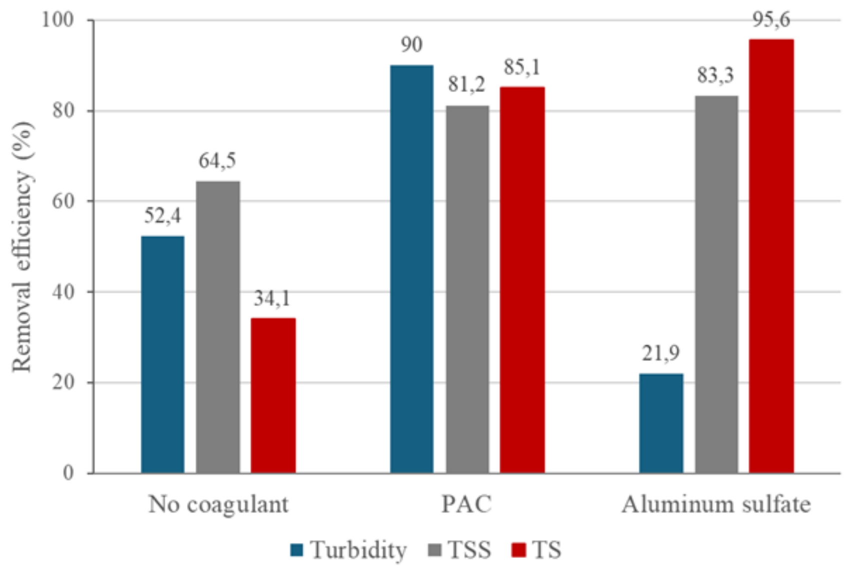

Figure 1. Turbidity, total suspended solids (TSS), and total solids (TS) removal efficiencies (%) in on-site tests. Font: Prado et al. (2023).

Regarding turbidity removal, polyaluminum chloride (PAC) demonstrated the highest efficiency, achieving a 90% reduction in turbidity (Figure 1). In contrast, aluminum sulfate exhibited the lowest turbidity removal efficiency (21.9%), which was even inferior to the efficiency observed without coagulant addition (52.4%) (Figure 1).

The suboptimal turbidity removal observed during on-site tests can be attributed to the absence of an agitator capable of providing the ideal mixing time and velocity gradient, as utilized in the Jar test. Yukselen & Gregory (2002), in their study on floc rupture and rearrangement, found that applying a very high-velocity gradient causes flocs to break within seconds. Even after the mixing intensity decreases, the flocs cannot fully recover their original size (Yukselen & Gregory, 2002). This highlights the importance of controlled mixing conditions to optimize coagulation efficiency in real-world applications.

Another factor that may have impacted the low turbidity removal using $Al_2(SO_4)_3$ was the variation in pH. In the preliminary tests, the average pH value was 8.06 for the 40 mg L^{-1} dosage, while in the on-site test, the average pH was 7.88. Voltan (2007) constructed a coagulation diagram for evaluating water supplies using a dosage of 40 mg L^{-1} of aluminum sulfate. At pH 6.6, the remaining turbidity was 4.66 UT; at pH 6.5, the remaining turbidity was 12.5 UT (268% increase in remaining turbidity) (Voltan, 2007).

Although the characteristics of the water to be treated in this study are different, Voltan's investigation (2007) is important for showing the effect of pH variation on the coagulation process and, consequently, on the formation of the flotation.

PAC was also the coagulant with the highest turbidity removal efficiency in the study carried out by Santos et al. (2014). Santos et al. (2014) achieved a turbidity removal efficiency of 96.5% using a dosage of 150 mgL-1 of PAC and a pH of 8 in the primary treatment of petrochemical industry effluent.

Concerning the relevant effluent discharge legislation, CONAMA Resolution 430/2011 (Brasil, 2005) does not have limits for the turbidity and TSS concentration of the final effluent, so CONAMA Resolution 357/2005 and COPAM/CERH-MG Normative Deliberation 01/2008 (Minas Gerais, 2008) were used for comparative analysis, considering discharge into Class II water bodies. In both regulations, the maximum turbidity value for discharge under these conditions is 100 NTU. According to the data from the on-site tests, the final effluent turbidity was higher than the maximum limit when the flotator was operated without the prior addition of coagulants. However, in the tests carried out with the addition of PAC and aluminum sulfate, the average final turbidity value remained below the limit set by federal and state legislation.

Concerning the TSS parameter, it should be noted that COPAM/CERH-MG Normative Deliberation No. 01/2008 establishes a maximum limit of 100 mg.L^{-1} in Class II fresh waters. The effluent data from the on-site tests showed that this limit was unmet. However, it should be noted that the industrial WWTP has a secondary treatment system consisting of an activated sludge unit, in which this compound will be removed, along with the organic and nitrogenous material present in the sanitary sewage produced in the industry.

Economic evaluation

Table 3 compares the weekly operating costs of the DAF unit with the prior application of PAC and $Al_2(SO_4)_3$ coagulants in the equalization tanks of the industry studied. These estimates were made using Equations 1 and 2 and considering the coagulant values for October 2023 from the company QumisulSC Brasil.

Table 3. Comparison of the costs of applying PAC and aluminum sulfate coagulants in the operational routine of the industrial WWTP. Source: Prado et al. (2023).

Characteristics	PAC	Aluminum sulphate
Maximum wastewater flow	24 m³.week^{-1}	24 m³.week^{-1}
Coagulant concentration	0.0181 L.m^{-3}	0.04 kg.m^{-3}
Commercial price of coagulant	R$ 15.80 L^{-1}	R$ 17.60 kg^{-1}
Total weekly cost	R$ 6.87.week^{-1}	R$ 16.90.week^{-1}

According to the economic comparison shown in Table 3, PAC was the most viable alternative, representing a weekly cost for the industry of R$ 6.87. Azhar, Haron & Ismail (2022) also concluded that PAC was the most cost-effective coagulant, compared with Al2(SO4)3, in operating a full-scale water treatment plant in Johor, Malaysia. These authors highlighted that PAC could increase the coagulation performance by requiring a lower dosage amount, producing less residual aluminum (Azhar, Haron & Ismail, 2022).

Conclusions

This study contributes to environmental protection by optimizing wastewater treatment processes, reducing the discharge of harmful pollutants into water bodies, and minimizing the environmental impact of industrial effluents.

PAC was the most cost-effective option, offering an efficient and economical solution to enhance preliminary treatment and reduce the aluminum and silica load on the subsequent biologically activated sludge process. Using PAC as a coagulant helps lower overall chemical consumption and sludge production, promoting more sustainable industrial practices.

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