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Evaluation of turbidity removal at the Seminário Water Treatment Plant: a comparative analysis of PAC and aluminum sulfate coagulants

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Avaliação da remoção de turbidez na ETA Seminário: análise comparativa entre os coagulantes PAC e sulfato de alumínio

RESUMO

Objetivo - Realizar a análise estatística da eficiência do coagulante policloreto de alumínio (PAC), utilizado na Estação de Tratamento de Água (ETA) Seminário, localizada no município de Mariana, Minas Gerais, em comparação ao coagulante sulfato de alumínio ($Al_2(SO_4)_3$), empregado na estação até o ano de 2020, com foco específico na remoção da turbidez da água. Adicionalmente, objetiva-se avaliar a conformidade dos valores de turbidez da água tratada registrados com o padrão de potabilidade vigente para este parâmetro, comparando o desempenho dos coagulantes em relação ao atendimento dos critérios normativos.

Metodologia - Os dados de turbidez da água tratada com ambos os coagulantes foram obtidos junto aos funcionários responsáveis pela ETA Seminário. Considerando que os registros foram realizados manualmente, procedeu-se à sua digitalização para posterior tratamento estatístico. A análise estatística foi conduzida por meio do teste de Kolmogorov-Smirnov (KS), a fim de verificar a aderência dos dados à distribuição normal. Em seguida, aplicou-se o teste não paramétrico U de Mann-Whitney para identificar possíveis diferenças estatisticamente significativas entre as medianas das amostras associadas ao uso do PAC e do $Al_2(SO_4)_3$.

Originalidade/relevância - Observa-se uma escassez de estudos que avaliem, de forma comparativa e por meio de métodos estatísticos, a eficiência desses dois coagulantes com base em extensos conjuntos de dados operacionais, especialmente no que se refere à redução de turbidez. A relevância acadêmica do estudo reside na aplicação de métodos estatísticos a dados operacionais reais, ampliando o conhecimento sobre o desempenho de coagulantes em contextos práticos e oferecendo subsídios para pesquisas futuras na área de tratamento de água e saneamento.

Resultados - O teste KS indicou que as amostras não seguem uma distribuição normal. O teste U de Mann-Whitney mostrou que a mediana da amostra referente à turbidez após o tratamento com o PAC é estatisticamente menor que a mediana da amostra da turbidez após o tratamento com o $Al_2(SO_4)_3$, evidenciando maior eficiência do PAC na remoção de turbidez da água. Relativo ao padrão de potabilidade, a análise demonstrou que o PAC apresentou um desempenho superior, com maior proporção de resultados em conformidade, enquanto o uso do $Al_2(SO_4)_3$ resultou em frequentes não conformidades e valores críticos.

Contribuições teóricas/metodológicas - O estudo contribui teoricamente ao evidenciar, com base em dados empíricos, a eficiência do PAC em relação ao $Al_2(SO_4)_3$ na redução de turbidez da água em uma estação de tratamento. Metodologicamente, o trabalho oferece um modelo replicável de avaliação comparativa de coagulantes a partir de registros operacionais.

Contribuições sociais e ambientais - A compreensão sobre qual dos dois coagulantes apresenta maior eficácia na remoção de partículas suspensas da água, representadas pela turbidez, pode influenciar de forma direta a tomada de decisão quanto à sua adoção em uma ETA e conduzir a um processo de tratamento de água mais refinado, contribuindo para a produção de água potável de maior qualidade, o que impacta positivamente a saúde e a qualidade de vida da população consumidora.

PALAVRAS-CHAVE: Policloreto de alumínio. Sulfato de alumínio. Turbidez.

Evaluation of turbidity removal at the Seminário WTP: a comparative analysis of PAC and aluminum sulfate coagulants

ABSTRACT

Objective - To perform a statistical analysis of the efficiency of the aluminum polychloride (PAC) coagulant used at the Seminário Water Treatment Plant (WTP), located in the municipality of Mariana, Minas Gerais, in comparison with aluminum sulfate ($Al_2(SO_4)_3$), which was used at the plant until 2020, with a specific focus on turbidity removal. Additionally, the study aims to assess the compliance of recorded treated water turbidity values with the current drinking water standards for this parameter, comparing the performance of the coagulants in meeting regulatory criteria.

Methodology - Treated water turbidity data for both coagulants were obtained from the personnel responsible for the operation of the Seminário WTP. As the records were collected manually, they were digitized for subsequent statistical processing. Statistical analysis was conducted using the Kolmogorov-Smirnov (KS) test to verify data adherence to a normal distribution. Subsequently, the nonparametric Mann-Whitney U test was applied to identify possible statistically significant differences between the medians of the samples associated with the use of PAC and $Al_2(SO_4)_3$.

Originality/Relevance - There is a scarcity of studies that comparatively evaluate, through statistical methods, the efficiency of these two coagulants based on extensive operational datasets, particularly regarding turbidity reduction. The academic relevance of this study lies in the application of statistical methods to real operational data, expanding knowledge about coagulant performance in practical contexts and providing support for future research in the fields of water treatment and sanitation.

Results - The KS test indicated that the samples do not follow a normal distribution. The Mann-Whitney U test showed that the median turbidity after treatment with PAC is statistically lower than the median turbidity after treatment with $Al_2(SO_4)_3$, demonstrating the greater efficiency of PAC in turbidity removal. With respect to drinking water standards, the analysis showed that PAC exhibited superior performance, with a higher proportion of compliant results, whereas the use of $Al_2(SO_4)_3$ resulted in frequent noncompliance and critical values.

Theoretical/Methodological Contributions - The study contributes theoretically by demonstrating, based on empirical data, the greater efficiency of PAC compared to $Al_2(SO_4)_3$ in reducing water turbidity at a water treatment plant. Methodologically, the work provides a replicable model for the comparative evaluation of coagulants using operational records.

Social and Environmental Contributions - Understanding which of the two coagulants is more effective in removing suspended particles from water, represented by turbidity, can directly influence decision-making regarding their adoption at a WTP and lead to a more refined water treatment process. This contributes to the production of higher-quality drinking water, positively impacting public health and the quality of life of the consuming population.

KEYWORDS: Aluminum polychloride. Aluminum sulfate. Turbidity.

Evaluación de la remoción de turbidez en la ETA Seminário: análisis comparativo entre los coagulantes PAC y sulfato de alumínio

RESUMEN

Objetivo - Realizar el análisis estadístico de la eficiencia del coagulante policloruro de aluminio (PAC), utilizado en la Estación de Tratamiento de Agua (ETA) Seminário, ubicada en el municipio de Mariana, Minas Gerais, en comparación con el coagulante sulfato de aluminio ($Al_2(SO_4)_3$), empleado en la estación hasta el año 2020, con un enfoque específico en la remoción de la turbidez del agua. Adicionalmente, se busca evaluar la conformidad de los valores de turbidez del agua tratada registrados con el estándar de potabilidad vigente para este parámetro, comparando el desempeño de los coagulantes en relación con el cumplimiento de los criterios normativos.

Metodología - Los datos de turbidez del agua tratada con ambos coagulantes fueron obtenidos junto a los funcionarios responsables de la ETA Seminário. Considerando que los registros fueron realizados de forma manual, se procedió a su digitalización para su posterior tratamiento estadístico. El análisis estadístico se llevó a cabo mediante la prueba de Kolmogórov-Smirnov (KS), con el fin de verificar la adherencia de los datos a una distribución normal. Posteriormente, se aplicó la prueba no paramétrica U de Mann-Whitney para identificar posibles diferencias estadísticamente significativas entre las medianas de las muestras asociadas al uso del PAC y del $Al_2(SO_4)_3$.

Originalidad/Relevancia - Se observa una escasez de estudios que evalúen, de manera comparativa y mediante métodos estadísticos, la eficiencia de estos dos coagulantes con base en extensos conjuntos de datos operativos, especialmente en lo que respecta a la reducción de la turbidez. La relevancia académica del estudio reside en la aplicación de métodos estadísticos a datos operativos reales, ampliando el conocimiento sobre el desempeño de los coagulantes en contextos prácticos y ofreciendo insumos para futuras investigaciones en el área de tratamiento de agua y saneamiento.

Resultados - La prueba KS indicó que las muestras no siguen una distribución normal. La prueba U de Mann-Whitney mostró que la mediana de la muestra correspondiente a la turbidez después del tratamiento con PAC es estadísticamente menor que la mediana de la muestra de turbidez después del tratamiento con $Al_2(SO_4)_3$, lo que evidencia una mayor eficiencia del PAC en la remoción de la turbidez del agua. En relación con el estándar de potabilidad, el análisis demostró que el PAC presentó un desempeño superior, con una mayor proporción de resultados conformes, mientras que el uso de $Al_2(SO_4)_3$ resultó en frecuentes no conformidades y valores críticos.

Contribuciones teóricas/metodológicas - El estudio contribuye teóricamente al evidenciar, con base en datos

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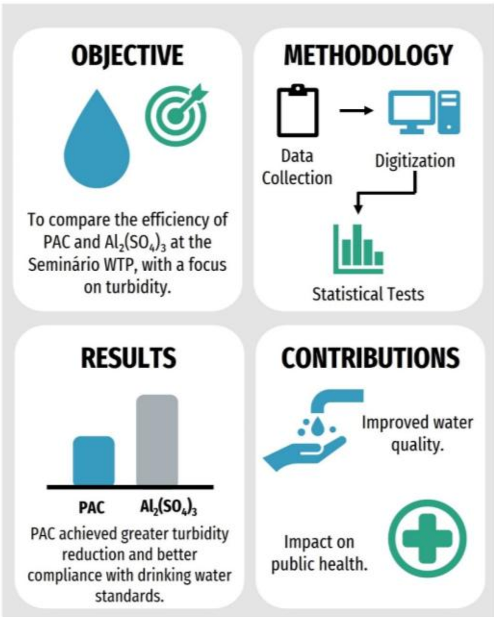
empíricos, la eficiencia del PAC en relación con el $Al_2(SO_4)_3$ en la reducción de la turbidez del agua en una estación de tratamiento. Metodológicamente, el trabajo ofrece un modelo replicable de evaluación comparativa de coagulantes a partir de registros operativos.

Contribuciones sociales y ambientales - La comprensión de cuál de los dos coagulantes presenta mayor eficacia en la remoción de partículas suspendidas en el agua, representadas por la turbidez, puede influir de manera directa en la toma de decisiones respecto a su adopción en una ETA y conducir a un proceso de tratamiento de agua más refinado, contribuyendo a la producción de agua potable de mayor calidad, lo que impacta positivamente en la salud y la calidad de vida de la población consumidora.

PALABRAS CLAVE: Policloruro de aluminio. Sulfato de aluminio. Turbidez.

GRAPHICAL ABSTRACT



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1 INTRODUCTION

Water is an invaluable natural resource for humans, essential for survival and daily activities. To ensure safe consumption, it is necessary to comply with potability standards that guarantee the water is free from impurities, pathogenic microorganisms, and other contaminants potentially harmful to human health. Therefore, water treatment prior to distribution to the population is essential, especially when the water is sourced from surface water bodies, such as rivers, which are susceptible to various sources of pollution.

The infrastructure, comprising civil structures, equipment, and various materials used for the treatment and distribution of potable water to the population, constitutes the water supply system for human consumption. Within this system, facilities that treat water to meet potability standards are referred to as Water Treatment Plants (WTPs). In Brazil, these standards are regulated by Portaria GM/MS Nº 888, of May 4, 2021, a ministerial ordinance issued by the Brazilian Ministry of Health (Brasil, 2021).

Water treatment aims to improve its physical, chemical, and biological properties, which comprise the Water Quality Index (WQI), an instrument used to describe water quality and ensure that it is suitability for human consumption (Chidiac *et al.*, 2023). This process occurs through stages that generally include coagulation, flocculation, sedimentation, filtration, disinfection, pH correction, and fluoridation (Trifirò; Zanirato, 2024).

According to Pandey and Khan (2022), during the coagulation stage, coagulants are added to water to remove colloidal particles that contribute to turbidity, color, taste, and odor. These coagulants destabilize suspended solids in the liquid, enabling their aggregation into larger flocs. These flocs are subsequently removed during subsequent treatment stages, resulting in a significant reduction in water turbidity and other parameters.

The coagulants used in this process may be organic or inorganic. Among organic coagulants, compounds such as tannin, chitosan, *moringa oleifera*, and *aloe vera* show potential as coagulating and flocculating agents, offering environmental advantages related to the reduction in the use of conventional chemical inputs and the mitigation of impacts associated with water treatment (Borri, Freire,Boina, 2014; Martins, Oliveira, Guarda, 2014).

The inorganic coagulant most commonly used in WTP is aluminum sulfate ($Al_2(SO_4)_3$). In addition to this compound, sodium aluminate ($NaAlO_2$), aluminum chloride ($AlCl_3$), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), and ferrous sulfate ($FeSO_4$) are also widely employed (Pandey; Khan, 2022). It is noteworthy that, in recent years, polyaluminum chloride (PAC) has become established as an efficient coagulant, offering advantages over $Al_2(SO_4)_3$, such as lower required dosage, reduced sludge generation, and better performance over a broader range of pH and temperature, as reported by Kumar and Balasundaram (2017) and Dutta (2020).

Turbidity is one of the main parameters evaluated to assess water quality, as it reflects the presence of suspended particles, known as Total Suspended Solids (TSS), which may include microorganisms, pollutants, sediments and microplastics, among others. The low natural sedimentation capacity of TSS necessitate the use of coagulants during treatment to facilitate their removal within a short time interval, making the selection of an effective coagulant essential to ensure proper process performance (Kumar and Balasundaram, 2017).

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The reduction of turbidity, therefore, contributes significantly not only to improving the visual appearance of water, making it clearer, more appealing for consumption, but also to ensuring sanitary safety, protecting the population against diseases and promoting confidence in the water supply system.

According to Gonçalves (2017), statistical analysis primarily aims to infer conclusions about an entire population from representative samples. To this end, tools such as statistical tests are employed, with particular emphasis on hypothesis testing, which enable assessment of whether a hypothesis is supported by sample data and thereby assists decision-making. These tests, for example, allow, the comparison of coagulant performance and the determination of whether the observed differences are statistically significant.

There is a lack of studies that compare the effectiveness of PAC and $Al_2(SO_4)_3$ in reducing water turbidity through statistical approaches. Identifying which coagulant exhibits better performance in the removal of suspended particles may have a direct impact on the choice of input to be adopted in water treatment plants, thereby promoting greater efficiency in the water treatment process.

The Seminário WTP is located in the municipality of Mariana, in the state of Minas Gerais (MG), Brazil, at the geographic coordinates 20.385444° S latitude and 43.410073° W longitude (Google, 2023), and is operated by the Autonomous Water and Sewerage Service (*Serviço Autônomo de Água e Esgoto* – SAAE) of Mariana. The treatment plant has a nominal capacity of 18 L s^{-1} and supplies the neighborhoods of São José (Chácara), Cabanas, São Pedro, and Dom Viçoso Street (SAAE, 2023).

The water arriving at the treatment plant (raw water) originates from the Seminário Spring, a surface water source, and is conveyed to the facility through two transmission pipelines, passing through a screening system. The water treatment plant comprises 13 flocculation chambers, one conventional sedimentation tank, five rapid filters, and one reservoir with a storage capacity of approximately 60 m³. For several years, the Seminário WTP used $Al_2(SO_4)_3$ as the chemical coagulant, and in 2020 it was replaced by PAC.

2 OBJECTIVE

2.1 General objective

This study aimed to analyze, based on statistical inference, whether the use of the PAC coagulant promoted a significant change in the removal of turbidity from treated water at the Seminário WTP, compared to treatment using $Al_2(SO_4)_3$.

2.2 Specific objectives

- To apply statistical techniques for sample distribution analysis and hypothesis testing;
- To compare the efficiency of the PAC and $Al_2(SO_4)_3$ coagulants in water turbidity removal;
- To verify the compliance of the collected data with the regulated turbidity standards;
- To evaluate which coagulant best adhered to the regulatory limits.

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3 METHODOLOGY

3.1 Data Collection and Systematization

To analyze the performance of the PAC coagulant relative to $Al_2(SO_4)_3$ in turbidity removal after water treatment, operational data from the Seminário WTP were collected for the period from 2018 to 2022.

The data were provided by the professionals responsible for operating the WTP and consisted of station control spreadsheets in which information such as raw water and treated water turbidity was manually recorded, at 2-hour intervals over 24 hours. The data for treatment with $Al_2(SO_4)_3$ cover the period from January 1, 2018, to July 21, 2020, totaling 10.903 records, whereas the data for treatment with PAC cover the period from July 22, 2020, to December 2022, totaling 10.404 records.

Since the data were recorded manually, it was necessary to digitize them. This process was carried out using the nanonets.com website, which enabled the conversion of handwritten tabular data into a format compatible with Microsoft Excel. The treated water turbidity data for each coagulant were separated and organized into spreadsheets in chronological order to facilitate their use and consultation.

Subsequently, a thorough review of each data point was conducted to correct any potential errors resulting from website's artificial intelligence (AI) driven data digitalization. It is worth noting, however, that the manual nature of the original measurements and records constitutes a limitation of the present study, as this type of procedure may be subject to operational variability, recording errors, and inconsistencies associated with human factors.

Although the data review stage was conducted rigorously, the possibility of residual bias cannot be completely ruled out. Therefore, the results obtained should be interpreted in light of this limitation, while recognizing that the substantial volume of data analyzed tends to mitigate potential isolated distortions and enhance the robustness of the analyses performed.

3.2 Analysis of data normality

It was necessary to assess whether the data followed a normal distribution, a fundamental step in selecting the most appropriate statistical method for sample analysis, given that normality is an assumption of many statistical tests. For this purpose, the Kolmogorov-Smirnov (KS) test was performed. As a nonparametric test, it does not require strict assumptions about the shape of the data distribution, which confers versatility in statistical analysis (Corder; Foreman, 2014).

The KS test is a hypothesis test, a procedure used to evaluate the validity of an assumption about a population parameter. Such tests are based on an initial hypothesis, known as the null hypothesis (H_0), which represents the absence of an effect or significant difference. In parallel, an alternative hypothesis (H_1) is formulated, suggesting the existence of a relevant effect or difference. Based on sample data, the statistical test is applied to assess the plausibility of H_0, considering a previously established significance level (α). If the statistical evidence is

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sufficient to reject H_0, H_1 is accepted as the most likely explanation for the observed data (Assis; Sousa; Linhares, 2020).

According to DeGroot (1986), the KS test evaluates the H_0 that the empirical cumulative distribution function of the sample corresponds to the theoretical cumulative distribution function. H_0 is rejected when the test statistic, represented by $n^{1/2}D_n^*$, exceeds a tabulated critical value c, indicating that the data do not follow the expected distribution. In this context, the test proves to be an important tool for assessing data normality.

The test was carried out using Excel software, considering turbidity data after water treatment with the $Al_2(SO_4)_3$ coagulant and with the PAC coagulant. The significance level adopted for the test was 5% ($\alpha = 0.05$). It is worth noting that the chosen α reflects the probability of rejecting H_0 when it is, in fact, true. An α of 5% represents a 95% confidence level in the results obtained (Shrestha, 2019). In addition, normal probability plots for both samples were generated using RStudio software.

Outliers, defined by Fitrianto *et al.* (2022) as observations that deviate considerably from other observations in a dataset, were removed only from the graphical representations in order to improve the visual clarity of the distributions. Data sets related to water treatment often contain many outliers. Various environmental factors in the collection area may influence recorded values, leading to anomalous data points (Kulanuwat *et al.*, 2021).

The outlier data were not removed from the analyses because, although they often indicate atypical behavior or potential errors, they do not necessarily reflect data flaws. Moreover, excluding these records could result in the loss of relevant information for the interpretation and understanding of the phenomena under study.

3.3 Analysis of the effect of coagulants on turbidity

Because the data did not follow a normal distribution, as shown in the results, the nonparametric Mann-Whitney U test was applied. According to Nachar (2008), this is a hypothesis test that compares two independent samples without assuming a specific distribution for them.

In this test, H_0 assumes that the medians of the two independent samples being compared are equal. In contrast, H_1 assumes that one median is greater than the other. H_0 is rejected when the calculated test statistic z is greater than or equal to the tabulated critical z value (Nachar, 2008). The test was performed in Microsoft Excel at a significance level of 5%, allowing assessment of which coagulant was more efficient at removing water turbidity after treatment.

3.4 Verification of compliance with the turbidity standard

The evaluation of compliance with the treated water turbidity standard was conducted based on the criteria established by the regulation in force during each analyzed period. For the period from January 2018 to April 2021, the reference was the *Portaria de Consolidação GM/MS nº 5, of September 28, 2017* (Brasil, 2017), which at that time governed water quality standards. For the period from May 2021 to December 2022, the parameters defined by *Portaria GM/MS*

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nº 888, of May 4, 2021 (Brasil, 2021), were adopted, which were already in effect during that period.

The ordinance GM/MS nº 888/2021 establishes that the maximum permissible value (MPV) for turbidity in water from surface sources, after rapid filtration, is 0,5 nephelometric turbidity unit (NTU) in 95% of the samples analyzed monthly, with a tolerance of up to 1,0 NTU for the remaining 5%. *Portaria de Consolidação* GM/MS nº 5/2017, in turn, set progressive targets for achieving the MPV of 0,5 NTU for rapid filtration systems, as shown in Table 1.

Table 1 - Turbidity standard for rapidly filtered water: progressive targets

Ordinance	MPV of 0,5 NTU	MPV of 1,0 NTU
GM/MS nº 5/2017	In at least 25% of the monthly collected samples, by the end of the first year after the ordinance was published. In at least 50% of the monthly collected samples, by the end of the second year after the ordinance was published. In at least 75% of the monthly collected samples, by the end of the third year after the ordinance was published. In at least 95% of the monthly collected samples, by the end of the fourth year after the ordinance was published.	In the remaining monthly collected samples.

Source: Adapted from Brasil (2017).

Thus, the percentages of monthly collected samples with values less than or equal to 0,5 NTU and greater than 1,0 NTU were calculated in Excel for the treatment with $Al_2(SO_4)_3$ and PAC over the analyzed period, and the results were organized into tables.

4 RESULTS AND DISCUSSION

4.1 KS Test

When performing the KS test for the data corresponding to turbidity after treatment with $Al_2(SO_4)_3$, the test statistic $n^{1/2}D_n^*$ was 0,331. For the turbidity data resulting from treatment with PAC, the test indicated $n^{1/2}D_n^*$ equal to 0,302. The critical value for both samples was 0,013. In addition to these values, Table 2 shows the adopted α and the sample sizes (n).

Table 2 - KS Test results

Coagulant	α	n	$n^{1/2}D_n^*$	c
PAC	0,05	10.404	0,302	0,013
$Al_2(SO_4)_3$	0,05	10.903	0,331	0,013

Source: Author's own.

Since $n^{1/2}D_n^* > c$ for both the sample corresponding to turbidity treated with $Al_2(SO_4)_3$ and the sample corresponding to turbidity treated with PAC, H_0 is rejected. Thus, it is concluded that the samples do not follow a normal distribution. Therefore, it is necessary to proceed with the analysis using a nonparametric statistical method.

The standard probability plot (Figure 1) shows the distribution of treated water turbidity values for PAC and $Al_2(SO_4)_3$ in relation to a theoretical normal distribution. The thin

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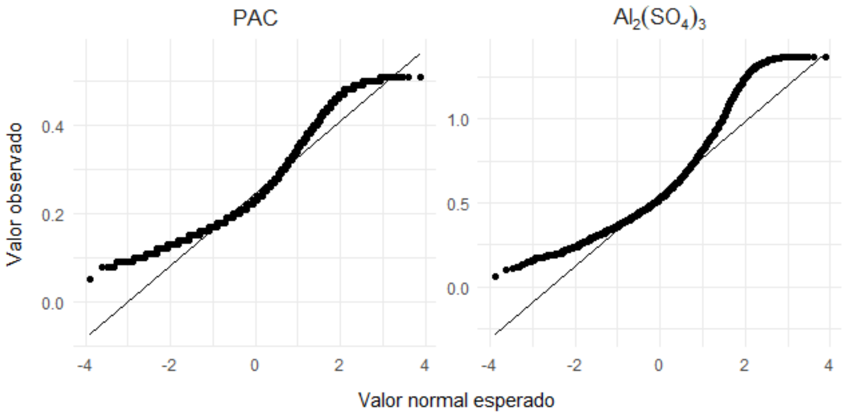
continuous line represents the reference line for a normal distribution, while the curve formed by black dots corresponds to the distribution of the observed values.

Graphic 1 - Comparison of the turbidity data distribution curves after treatment with PAC and $Al_2(SO_4)_3$ in relation to the theoretical normal distribution line



Source: Author's own.

It can be observed that most points deviate from the standard distribution line, indicating that the data do not conform to this distribution. This behavior corroborates the KS test result, which indicated that the data are not normally distributed.

4.2 Mann-Whitney U Test

The application of the Mann-Whitney U test at a significance level of 5% yielded a |calculated z| value of 105,61, while the |tabulated z| value was 1,64, as shown in Table 3.

Table 3 - Mann-Whitney U Test results

	Result
|calculated z|	105,61
|tabulated z|	1,64

Source: Author's own.

Since |calculated z| > |tabulated z|, H_0 is rejected, and H_1 that one median is greater than the other is accepted. Therefore, there is a statistically significant difference between the medians. The median of the water turbidity sample treated with PAC was 0,24 NTU, while the median of the turbidity sample after treatment with $Al_2(SO_4)_3$ was 0,55 NTU. Thus, it is evident that the median for the PAC sample was statistically lower than that for $Al_2(SO_4)_3$, suggesting that PAC was more efficient at removing turbidity from water at the Seminário WTP.

The greater efficiency of PAC observed in this study is supported by the literature, which highlights its superior performance in coagulation processes compared to $Al_2(SO_4)_3$. From an environmental perspective, the use of PAC has been associated with lower sludge production and reduced residual aluminum in treated water, which may help minimize environmental impacts associated with waste disposal (Dutta, 2020).

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From an economic perspective, the higher coagulation efficiency and the need for lower dosages reported by Azhar, Haron, and Ismail (2022) tend to reduce input consumption and operational costs over time. From a social perspective, greater consistency in meeting turbidity regulatory standards directly impacts the safety and reliability of public water supply, a key aspect for protecting public health.

In the Brazilian context, characterized by high regional heterogeneity, budgetary constraints, and challenges in achieving universal basic sanitation, selecting more efficient and environmentally suitable coagulants is a strategic role priority, especially in public water supply systems, where operational efficiency and regulatory compliance directly affect the population's quality of life.

Thus, the results of this study reinforce the notion that adopting PAC may represent not only a technical improvement but also an advancement in sustainability and the quality of sanitation services.

4.3 Analysis of compliance with the turbidity standard

To verify compliance with the MPV for turbidity for the years 2018, 2019, and 2020, a period during which $Al_2(SO_4)_3$ was used at the Seminário WTP, the targets shown in Table 1, corresponding to *Portaria de Consolidação* GM/MS nº 5/2017, in effect at the time, were considered. Accordingly, the percentage of collected samples with turbidity values below 0,5 NTU and above 1,0 NTU was calculated for each month of the analyzed period. Table 4 shows the results obtained for treatment with the $Al_2(SO_4)_3$ coagulant.

Table 4 - Percentage of collected samples with values ≤ 0,5 NTU and > 1,0 NTU for treatment with $Al_2(SO_4)_3$

Month	2018		2019		2020	
	(1)	(2)	(1)	(2)	(1)	(2)
January	38,61%	62,44%	71,39%	5,71%	26,63%	40,32%
February	26,22%	10,74%	43,12%	22,58%	29,57%	19,05%
March	16,62%	20,61%	42,23%	15,57%	38,48%	28,77%
April	9,89%	24,45%	24,44%	7,35%	55,28%	4,35%
May	19,51%	11,78%	43,48%	5,29%	49,45%	0,54%
June	0,00%	99,43%	46,35%	4,19%	79,21%	6,76%
July	0,00%	96,50%	53,54%	4,88%	94,35%	14,29%
August	22,16%	39,93%	57,79%	2,68%	-	-
September	36,39%	18,47%	65,17%	10,48%	-	-
October	64,52%	18,18%	63,54%	1,52%	-	-
November	58,33%	16,67%	33,14%	29,39%	-	-
December	54,26%	26,71%	33,71%	13,79%	-	-

Source: Author's own.
Note: (1) ≤ 0,5 NTU; (2) > 1,0 NTU in the remaining samples.

It can be observed that in 2018, from March to August, the minimum percentage of 25% of samples with turbidity less than or equal to 0,5 NTU, as established in the progressive targets of *Portaria de Consolidação* GM/MS nº 5/2017, was not achieved. This result highlights difficulties in the water clarification process during this period.

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It should be noted that in June and July, none of the samples presented values within the 0,5 NTU limit, indicating a complete failure to meet the potability standard during these months. This unsatisfactory performance may be related to operational inefficiencies in the coagulation and filtration system, or to the need for adjustments in coagulant dosage and filter maintenance.

Furthermore, in all months of 2018, values exceeding 1,0 NTU were recorded, with February showing the lowest percentage of samples above this limit (10,74%) and June the highest (99,43%). These results indicate the need to review coagulation and filtration parameters, as well as to enhance operational control and preventive maintenance, in order to ensure process stability and compliance with potability standards.

In 2019, the minimum criterion of 50% of samples with turbidity up to 0,5 NTU was not met from February to June, as well as in November and December. Thus, a greater number of months were out of compliance compared to the previous year, highlighting difficulties in achieving the progressive targets established by the regulation.

As in the previous year, all months had samples with values exceeding 1,0 NTU. However, the number of samples above this limit decreased significantly, indicating a gradual improvement in treatment efficiency. The lowest percentage of samples exceeding the limit was recorded in October (1,52%), while the highest occurred in November (29,39%), suggesting that although overall performance improved, seasonal fluctuations in turbidity control persist. This variation may be related to both climatic factors and raw water quality, such as an increase in suspended solids due to higher rainfall typical of the period.

In 2020, from January to May, a minimum of 75% of samples with turbidity less than or equal to 0,5 NTU were not achieved. Again, in the analyzed months of that year, samples with values exceeding 1,0 NTU were observed. Among these months, January showed the highest frequency of such records (40,32%), while May showed the lowest (0,54%), representing the best performance of $Al_2(SO_4)_3$ over the entire analyzed period, from January 2018 to July 2020.

Thus, regarding the turbidity MPV of 0,5 NTU, it is observed that out of the 31 months analyzed, 18 did not reach the minimum required percentage of samples within this limit, corresponding to 58,06% of the total evaluated. This result highlights frequent noncompliance with the turbidity targets established by the *Portaria de Consolidação* GM/MS nº 5/2017, indicating that more than half of the analyzed period showed treatment efficiency below expectations.

Furthermore, among the 10.903 samples examined, 1.763 showed turbidity values exceeding 1,0 NTU, and in 100% of the months analyzed, samples with values above this limit were identified. This indicates a recurring noncompliance with the established standard, which may have compromised the final quality of treated water during specific periods.

To verify compliance with the turbidity MPV in treatment with PAC, the same procedure used for $Al_2(SO_4)_3$ treatment was applied from July 2020 to April 2021, during which the regulation in force was the *Portaria de Consolidação* GM/MS nº 5/2017. The results obtained are shown in Table 5.

Table 5 - Percentage of collected samples with values ≤ 0,5 NTU and > 1,0 NTU for treatment with PAC: evaluation based on *Portaria de Consolidação* GM/MS nº 5/2017

Month	2020		2021	
	(1)	(2)	(1)	(2)
January	-	-	98,34%	33,33%
February	-	-	95,72%	28,57%
March	-	-	98,37%	0,00%
April	-	-	100,00%	0,00%
May	-	-	-	-
June	-	-	-	-
July	94,17%	0,00%	-	-
August	92,13%	0,00%	-	-
September	95,53%	0,00%	-	-
October	94,10%	47,37%	-	-
November	90,41%	65,38%	-	-
December	93,13%	52,00%	-	-

Source: Author's own.
Note: (1) ≤ 0,5 NTU; (2) > 1,0 NTU in the remaining samples.

It is observed that, in the analyzed months of 2020, all met the minimum requirement of 75% of samples with turbidity less than or equal to 0,5 NTU. Between july and september, no samples with values exceeding 1,0 NTU were recorded, indicating operational efficiency and stability in the treatment process during this period.

However, between october and december, samples with turbidity above 1,0 NTU were again recorded, with november showing the highest occurrence (65,38%) of values exceeding the limit. This increase may be associated with the onset of the rainy season, when greater transport of particles and organic matter to the water sources occurs, increasing the suspended solids load and demanding stricter operational control at the WTP.

Regarding the year 2021, all evaluated months fully met the potability criterion, which establishes that at least 95% of the samples must have turbidity equal to or less than 0,5 NTU. This result demonstrates a significant improvement in water treatment efficiency compared to previous years, possibly reflecting enhancements in operational processes and the effect of the coagulant used.

In january and february, samples with turbidity above 1,0 NTU were recorded; however, the noncompliance percentages (33,33% and 28,57%, respectively) were substantially lower than those observed in 2020, indicating a trend toward stabilization of water quality. Notably, in april, all samples showed turbidity less than or equal to 0,5 NTU, with no values exceeding 1,0 NTU. This result demonstrates the consolidation of operational control.

For the period from may 2021 to december 2022, the regulation in force, *Portaria* GM/MS nº 888/2021, was adopted as a reference. This regulation establishes that, for turbidity in water treated by rapid filtration, at least 95% of the monthly samples must have values equal to or less than 0,5 NTU, with a limit of up to 1,0 NTU allowed for the remaining 5%. Based on this, to verify compliance with the turbidity MPV, the percentage of samples with values ≤ 0,5 NTU and > 1,0 NTU was calculated for each month. The results obtained are shown in Table 6.

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Table 6 - Percentage of collected samples with values ≤ 0,5 NTU and > 1,0 NTU for treatment with PAC: evaluation based on *Portaria de Consolidação* GM/MS nº 888/2021

Month	2021		2022	
	(1)	(2)	(1)	(2)
January	-	-	87,81%	59,09%
February	-	-	78,31%	9,72%
March	-	-	95,57%	0,00%
April	-	-	98,29%	0,00%
May	99,73%	0,00%	93,75%	4,35%
June	100,00%	0,00%	99,72%	0,00%
July	96,23%	7,14%	99,48%	0,00%
August	97,57%	11,11%	99,46%	0,00%
September	99,47%	0,00%	97,98%	0,00%
October	84,37%	25,86%	89,33%	34,29%
November	96,83%	18,18%	95,49%	18,75%
December	97,53%	22,22%	99,73%	0,00%

Source: Author's own. Note: (1) ≤ 0,5 NTU; (2) > 1,0 NTU in the remaining samples.

In 2021, the turbidity MPV of 0,5 NTU was only not met in October, when the achieved percentage was 84,37%, indicating a single episode of reduced treatment efficiency. This exception may be associated with seasonal influences, which increase the turbidity of raw water during the rainy season, requiring more precise adjustments in coagulant dosage and filtration unit operation.

It is also noted that in July, August, and from October to December, samples with turbidity above 1,0 NTU were recorded, with October showing the highest noncompliance percentage (25,86%). In contrast, May, June, and September had all samples within the 1,0 NTU limit, demonstrating efficient operation of the water treatment plant.

In 2022, compliance with the turbidity MPV of 0,5 NTU was not achieved in January, February, May, and October. Among these, February showed the lowest percentage of samples within the limit (78,31%), indicating a possible reduction in treatment efficiency during this period. Furthermore, samples with turbidity above 1,0 NTU were recorded in January, February, May, October, and November, with January showing the highest percentage of values exceeding this limit (59,09%). This behavior may be associated with the increased turbidity of raw water entering the treatment plant during periods of higher rainfall.

Thus, among the 30 months analyzed for treatment with PAC, 5 did not meet the minimum required percentage of samples with turbidity < 0,5 NTU, corresponding to 16,67% of the total period evaluated. This result shows that, although most months met the potability standards, there were still occasional periods of inefficiency in the clarification process.

Furthermore, of the 10.404 samples examined, 115 showed turbidity values exceeding 1,0 NTU, distributed over 15 months (50% of the period). This occurrence indicates that, even with generally satisfactory performance, there were recurring episodes of elevated turbidity, possibly associated with operational variations, raw water characteristics, or adverse climatic conditions. Table 7 compares the results obtained for the performance of PAC and $Al_2(SO_4)_3$ in meeting the turbidity potability standard.

Table 7 – Comparison of the performance of PAC and $Al_2(SO_4)_3$ in meeting the turbidity potability standard

Coagulant	Total months analyzed	Months exceeding the 0,5 NTU MPV	Months exceeding the 1,0 NTU MPV	Number of samples > 1,0 NTU
PAC	30	5	15	115
$Al_2(SO_4)_3$	31	18	31	1763

Source: Author's own.

In light of this scenario, it is evident that PAC outperformed $Al_2(SO_4)_3$ in meeting the turbidity regulatory standards, as with a higher compliance frequency under the MPV. The results indicate that PAC provided a more efficient coagulation process, reflected in the lower incidence of turbidity values above the regulatory limits and greater consistency in achieving the quality standards for treated water.

5 CONCLUSION

The coagulation step plays a fundamental role in water treatment, particularly in removing suspended particles, ensuring the quality and safety of water for human consumption. In this context, selecting the most effective coagulant is of utmost importance, as it optimizes impurity removal, ensures water potability, reduces costs and environmental impacts, improves the efficiency of subsequent processes, and prevents the formation of undesirable by-products.

In this context, the present study investigated the performance of PAC, the coagulant currently used at the Seminário WTP in Mariana/MG, compared to $Al_2(SO_4)_3$, the coagulant used at the same plant until 2020, in removing water turbidity. The comparative analysis used statistical methods to determine whether PAC would yield satisfactory results. Additionally, this study evaluated compliance with the turbidity standard for both coagulants by comparing the turbidity values of the collected samples with the turbidity MPV established by the regulations in force during each analyzed period.

The statistical analysis using the Mann-Whitney U test showed that the sample treated with PAC had lower median than the sample treated with $Al_2(SO_4)_3$. This finding demonstrates that PAC provided a more efficient coagulation process, resulting in greater capacity to remove particles that contribute to water turbidity.

The analysis of compliance with the turbidity MPV showed that PAC performed better than $Al_2(SO_4)_3$, as it remained within the regulatory limits more consistently. During the period analyzed with PAC applied in water treatment, only 5 months failed to reach the minimum requirement of 95% of samples with turbidity below 0,5 NTU. In contrast, for $Al_2(SO_4)_3$ treatment, it was observed that over the 18 months of the total evaluation period, the regulatory turbidity MPV was not met.

Regarding the 1,0 NTU MPV established by the regulations for the remaining collected samples, it was observed that in PAC treatment, turbidity values exceeding this limit were detected in 50% of the analyzed months. On the other hand, $Al_2(SO_4)_3$ showed lower performance, as samples with turbidity above 1,0 NTU were identified in 100% of the months evaluated.

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In summary, the results obtained in this study confirm the effectiveness of PAC in removing water turbidity, demonstrating its potential to ensure the potability and quality of water intended for human consumption.

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DECLARATIONS

AUTHOR CONTRIBUTIONS

Thais Mayara Rodrigues Gomes:
Data curation, formal analysis, investigation, methodology, writing - original draft, writing - critical review, final review and editing.

Elton Santos Franco:
Study conception and design, investigation, methodology, writing - critical review, and supervision.

Rafael Genaro:
Study conception and design, formal analysis, methodology, writing - critical review, and supervision.

Jairo Lisboa Rodrigues:
Methodology, writing - critical review, and supervision.

Núbia Aparecida de Aguilar:
Data curation, investigation, and writing - critical review.

DECLARATION OF CONFLICTS OF INTEREST

We**, Thais Mayara Rodrigues Gomes, Elton Santos Franco, Rafael Genaro, Jairo Lisboa Rodrigues, and Núbia Aparecida de Aguilar,** declare that the manuscript entitled ***"Evaluation of Turbidity Removal at the Seminário Water Treatment Plant: a Comparative Analysis between PAC and Aluminum Sulfate"***:

1. **Financial Relationships:** Has no financial relationships that could influence the results or interpretation of this work. No funding institution or entity was involved in the development of this study.
2. **Professional Relationships:** Has no professional relationships that could affect the analysis, interpretation, or presentation of the results. No professional relationship relevant to the content of this manuscript was established.
3. **Personal Conflicts:** Has no personal conflicts of interest related to the content of the manuscript. No personal conflict related to the content was identified.