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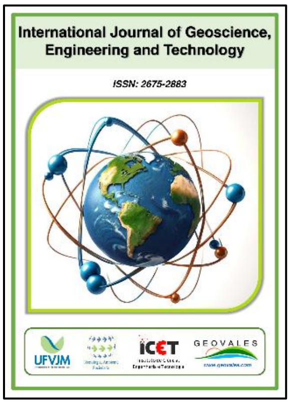

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Valuation of Lithium Mining Waste for Water Treatment: An Experimental Study and Broader Implications of Residual Aluminum Silicate (Al_2SiO_5) as an Artificial Zeolite

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Abstract

This study explored the potential of residual aluminum silicate (Al_2SiO_5), a mining byproduct collected from Brazilian Lithium Company (CBL), as a flocculating agent in the treatment of clay particle-laden waters. The experiments evaluated the material's ability to aggregate particles and reduce water turbidity under different conditions, acting as an artificial zeolite. Results demonstrated the effectiveness of residual aluminum silicate in flocculation, outperforming the control treatment. It was observed that the flocculant's performance was influenced by the medium's pH, being more efficient under alkaline conditions. This work suggests that residual aluminum silicate is a promising candidate for water treatment, but highlights the need for further understanding of its action and optimization for large-scale applications.

Keywords: Aluminum silicate, Waste, Water treatment, Artificial zeolite, Turbidity.

1. Introduction

Since the 19th century, technological innovations have directly driven the exploration and utilization of mineral resources, in Brazil and worldwide, especially in recent decades, regarding Lithium (Li). From the mid-1980s, this material became increasingly necessary for the evolution of science and materials technology. Currently, this element is used in the production of high-performance batteries and automotive greases, mental health medications, and many others (Ibsaine et al., 2024; Tao et al., 2024; Kim et al., 2025).

Therefore, it is undeniable that the exploration of this material, whether as lithium concentrate, lithium carbonate (Li_2CO_3), lithium hydroxide (LiOH), or in other molecular forms, is fundamental for the development of the human species in the coming decades, leading to an even greater and continuously growing increase in its effective extraction. According to World Bank estimates, presented by the Ministry of Mines and Energy in 2023, global demand for the ore is expected to increase by almost 1,000% by 2050 (Ibsaine et al., 2024).

According to data from the United States Geological Survey (USGS, 2023), identified lithium resources and reserves in Brazilian territory total approximately 1 billion tons of LCE (lithium carbonate equivalent), which positions Brazil as the holder of the seventh largest global reserve. Furthermore, the country consolidated itself as the fifth largest global producer of lithium carbonate in 2022, with an estimated annual production of 2,200 tons. These numbers reflect the growing strategic and economic interest in lithium in Brazilian territory, both for the domestic market and for exports, especially in a context of increasing demand for sustainable technologies (Oliveira, 2024; Lee et al., 2022).

However, precisely because of this advancement, a critical and environmental perspective must be directed towards this exploration so that it can occur sustainably, seeking solutions for the large quantity of waste generated. Lithium mining, especially from pegmatites, requires extraction and beneficiation processes that generate large volumes of solid waste and liquid effluents, often accompanied by by-products with toxic or persistent potential in the environment (Lottermoser, 2010; Ibsaine et al., 2023; Shin, 2024; Vera et al., 2023).

These processes result in the generation of aggregates containing silicates, metallic oxides, and sometimes potentially toxic elements, such as fluorine and heavy metals (Lottermoser, 2010). That is, the improper management of these mining by-products can compromise the quality of surface and groundwater bodies, in addition to generating long-term environmental liabilities. This article aims to add commercial and sustainable value to residual aluminum silicate (Al2SiO5), derived from the processing of spodumene from Brazilian Lithium Company (CBL), verifying its potential in water treatment, acting as an artificial zeolite (flocculating agent) based on experimental laboratory tests of different reactivity treatments of the residual aluminum silicate.

2. General Objective

The general objective of this work is to add commercial and sustainable value to the aluminum silicate residue (LiAlSi2O6), a by-product of lithium mining, by exploring its potential as a flocculating agent in the treatment of high-turbidity effluents as an artificial zeolite. The research aims to demonstrate how the valorization of this environmental liability contributes to the circular economy and to sustainability in the mining industry."

3. Theoretical Framework

Lithium (Li) is the lightest metal (0.534 g/cm³) and the third element in the periodic table. Its properties include high specific heat, the smallest ionic radius among alkaline earth metals, and a high electrochemical potential. Being highly reactive, lithium is not found pure in nature, being present in mineral deposits (pegmatites), salt deposits (evaporites), clay deposits (hectorites), or seawater (Brunhara and Braga, 2021).

Economically, this mineral is a fundamental element in various modern technologies, especially in the transport sector, where its application in batteries for electric and hybrid cars is crucial due to its high energy density and recharging capacity. In parallel, lithium and its compounds have several industrial applications. Lithium oxide (Li2O) is used in ceramics and glass, lithium hydroxide (LiOH) in the production of lubricating greases, and lithium carbonate (Li2CO3) in medications for bipolar disorder. In metallurgy, lithium is an alloying agent that increases the strength of other metals. This versatility transforms it into an engine of innovation, showing that its value goes far beyond battery production and impacts various fields.

However, lithium mining, although vital for the global energy transition and the production of advanced technologies, is an activity that poses considerable environmental challenges. In Brazil, the industrial production of lithium compounds is obtained directly from the spodumene mineral, which is an aluminosilicate (LiAlSi2O6) bearing lithium, with a content of 1 to 1.5% Li2O (Braga and Sampaio, 2008). Nationally, Companhia Brasileira de Lítio – CBL carries out underground mining of lithium ore, in pegmatites, in the municipalities of Araçuaí and Itinga-MG. The concentrated lithium (spodumene) produced is transferred to the CBL factory, in Divisa Alegre, MG, where it is transformed into lithium carbonate and hydroxide (Luz and Lins, 2010).

This mineral extraction, from hard rock deposits, such as pegmatites containing spodumene, is an energy and resource-intensive process, generating large volumes of solid waste and liquid effluents. These processes, aiming at the concentration of the strategic ore, can lead to multifaceted and systemic environmental degradation, affecting various environmental compartments and local communities (Yang et al., 2024).

The processing intensity, as mentioned, is due to the fact that spodumene and other lithium minerals generally occur as an accessory mineral in pegmatites. Although lithium occurs in different minerals, only spodumene, lepidolite, petalite, amblygonite, and montebrasite are used as commercial sources of lithium (Braga and Sampaio, 2008). The minerals mentioned above incorporate the silicate ion as an essential component of their crystalline structure. In the ore beneficiation process, to isolate lithium, the silicate — which is not the compound of interest to CBL — is separated and discarded as it has no added market value, becoming classified as mining waste and posing an environmental problem due to the large quantities generated.

These residues, often containing silicates, metallic oxides, and sometimes potentially toxic elements, represent a significant environmental challenge. Consequently, the improper management of these residual materials can compromise the quality of surface and groundwater bodies, in addition to generating long-term environmental liabilities (Lottermoser, 2010). Thus, the search for alternatives for the valorization of these residues is fundamental to mitigate the environmental impacts of lithium mining and promote a more sustainable development of the industry. Effluents and leachate from mining operations can contain chemical substances used in extraction processes, as well as toxic elements, such as heavy metals. This contamination compromises the quality of surface and groundwater, essential for agriculture and human consumption (Muniz and Oliveira-Filho, 2008). The release of large quantities of particulate matter can affect surrounding vegetation and populations near mining zones.

Given the growing demand for lithium and the associated environmental challenges, the adoption of sustainable practices and the principles of the circular economy are crucial. Waste valorization is not only an environmental imperative but also an economic opportunity that can generate profits, reduce environmental problems, create jobs, and increase sources of income. This multifaceted and interdisciplinary approach strengthens the justification for research that seeks to give an economic and social purpose to waste, such as this one, aligning environmental sustainability with socioeconomic development, reducing environmental liabilities (Kim et al., 2025). As illustrated in Figure (1).

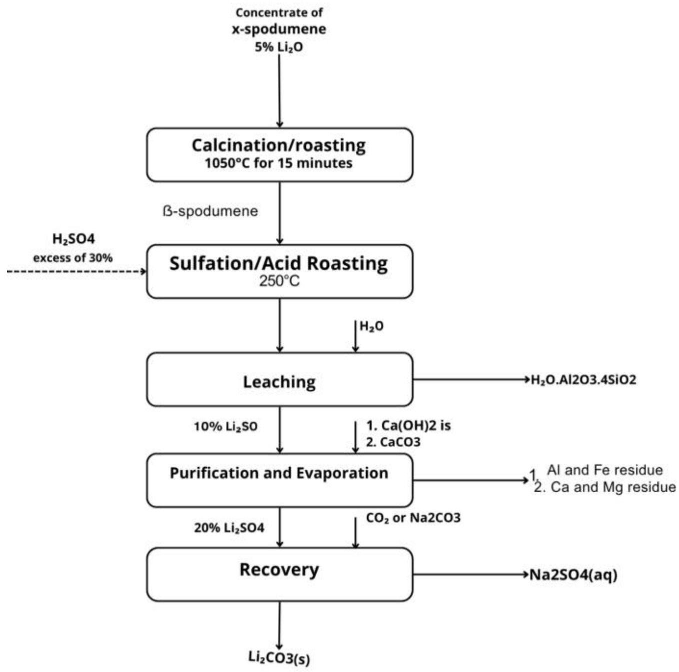

Figure 1 –Conventional acid process for the extraction of lithium from spodumene (Brunhara and Braga, 2021).

From a theoretical point of view, seeking an application and valorization of Al2SiO5, coagulation and flocculation are fundamental steps in conventional water and wastewater treatment processes, aiming at the removal of suspended solids, turbidity, and colloidal particles (Michelan, Santos and Rosa, 2022). Coagulation involves the destabilization of colloidal particles, often by adding coagulants that neutralize their surface charges, reducing electrostatic repulsion (Circuito Ambiental, 2022). Subsequent flocculation promotes the aggregation of these destabilized particles into larger and denser flocs, which can be easily removed by sedimentation or filtration. Lopes et al (2020) state that the efficiency of particle removal is significantly influenced by the processes of floc formation, growth, breakage, and rearrangement.

Aluminum silicate, whether in its residual form or as aluminum sulfate, has been widely studied and used as a flocculating agent in water and wastewater treatment (Vaz et al, 2010; Lopes et al, 2020; Fernandes et al, 2010; Yang et al., 2024). This is due to the fact that flocculation is an essential process that aims to aggregate suspended particles in water, forming larger and denser flocs that can be removed by sedimentation or filtration (Brazão, Silva and Vivacqua, 2021). Furthermore, pH optimization is a crucial factor for flocculant performance, and in many cases, alkaline conditions favor process efficiency (Alves, Borges and Fonceca, 2019). The use of residual aluminum silicate, such as that from lithium mining, presents a promising potential for water treatment, contributing to waste reduction and the development of more sustainable solutions.

According to Michelan, Santos and Rosa (2022), inorganic coagulants based on aluminum, such as aluminum sulfate, demonstrate high efficiency in removing true color (up to 97.53%) and contribute to the removal of apparent color in water. For Lopes et al (2020), sodium aluminate ($Al_2O_3 \cdot Na_2O$) also proved effective in turbidity removal, with an efficiency of 93% in dissolved air flotation processes. Kaolin, a hydrated aluminum silicate ($Al_2Si_2O_7 \bullet H_2O$), is frequently employed as a reagent to prepare turbid suspensions in flocculation tests (Lima Júnior and Abreu, 2018).

However, despite the effectiveness of aluminum-based coagulants, the presence of residual aluminum in treated water is a concern. Studies indicate that residual aluminum can be associated with health problems, such as brain lesions and neurodegenerative diseases like Alzheimer's (Freitas, Brilhante and Almeida, 2001). Residual aluminum can cause operational problems in water treatment plants, such as turbidity in the coagulation/flocculation stages and impairment of disinfection (Michelan et al, 2021). Thus, from the foregoing, it is clear that the valorization of residual aluminum silicate from lithium mining for water treatment, therefore, is not limited to its flocculating efficiency, but also lies in its potential to mitigate or reduce problems associated with conventional soluble aluminum-based coagulants, such as aluminum sulfate.

Following this overview, zeolites are microporous aluminosilicates with highly ordered crystalline structures. Their unique properties, including high cation exchange capacity (CEC) and selective adsorption capabilities, make them valuable materials in various applications, notably in water and wastewater treatment. They are effective in removing heavy metals, ammonia, and other contaminants from complex effluents, such as those generated by the mining industry (Kumari et al., 2024). The synthesis of zeolites from industrial waste, including mining waste, represents a sustainable approach to transform environmental liabilities into high-value-added products, that is, adding commercial value to a material that would initially be discarded (Ibsaine et al., 2024; Ibsaine et al., 2023; Machado et al., 2024; Eren, Türk and Arslanoğlu, 2024).

In addition to its role as a flocculant, aluminum silicate, especially residual, has been investigated as a precursor for the synthesis of artificial zeolites (Peñafiel-Villarreal and Martínez-Mañez, 2019). The synthesis of zeolites from waste, such as Al_2SiO_5 from lithium mining, represents an innovative approach to the valorization of these materials, transforming an environmental liability into a high-value-added product (Faria, 2017; Coelho, 2016). Therefore, the aptitude of zeolites to adsorb heavy metals, ammonia, and various other pollutants makes these materials promising for application in the treatment of complex effluents, especially those from mining activity. Scientific investigations in this field focus on optimizing synthesis conditions, with the aim of developing zeolites with specific structural and chemical properties that enhance their effectiveness in removing contaminants.

These mining activities, particularly lithium extraction, generate significant silicoaluminous waste (Santos, Nascimento E Pergher, 2018). These residues, rich in SiO_2 and Al_2O_3, are excellent alternative sources for zeolite synthesis (Magalhães, 2022). The alkaline hydrothermal activation method is commonly employed to synthesize zeolitic materials from these residues, involving the mixture of the residue with a strong alkaline solution (e.g., NaOH, KOH) and heating under controlled conditions (Izidoro and Fungaro, 2013). Thus, the ability to adapt zeolite properties through manipulation of synthesis parameters allows the creation of "tailor-made" materials for specific water treatment challenges. This means that, instead of a generic concept of "artificial zeolite," it is possible to develop them with optimized performance for specific contaminants or effluent conditions.

Zeolites synthesized from waste have promising applications in complex effluent treatment. For example, zeolites produced from coal fly ash have been successfully employed in the remediation of acid mine drainage, resulting in significant reductions in concentrations of metallic ions such as Pb, Cd, Mn, Cu, Cr, and As, in addition to an increase in pH (Fungaro and Izidoro, 2006). The removal mechanism involves cation exchange (metallic ions replacing Na+ in the zeolite structure) and the precipitation of metallic hydroxides/sulfates due to the increase in pH. According to Izidoro and Fungaro (2013), an additional advantage is that zeolites saturated with contaminants can be safely discarded or regenerated for reuse, further increasing their sustainability.

In parallel, their synthesis from these mining residues can offer an opportunity for secondary lithium recovery. Oliveira, Nascimento and Pergher (2018) observed that part of the lithium present in the residue can be incorporated into the zeolitic structure or remain in the synthesis water, indicating a potential for lithium recovery as a valuable by-product of the valorization process. This transforms residues from a single-purpose solution (water treatment) into a multipurpose solution (water treatment + lithium recovery).

In view of what was previously mentioned, the valorization of mining by-products, such as the residual aluminum silicate from lithium extraction, represents a fundamental pillar for the implementation of a circular economy model in the mining industry as a general panorama, for example, at CBL. Thus, instead of being discarded as waste, these materials are transformed into valuable resources for new applications, promoting the closing of cycles in industrial processes. Such an approach not only reduces the environmental burden associated with waste disposal (such as 'tailings dams' and contamination risks), but also decreases the dependence on raw materials for the production of chemicals for water treatment or zeolites, addressing new ways to perform flocculation and decantation. For this reason, this article is positioned as fundamental for new avenues in the sustainable area and also in the environmental sector.

4. Methodology

The present study was developed at Mining Waste Study Laboratory of the Institute of Science, Engineering and Technology (ICET) of the Federal University of Jequitinhonha and Mucuri Valleys (UFVJM) Mucuri campus.

4.1. Preparation of colloidal clay solution

Practically, it is worth noting that the evaluation of the flocculating potential of residual Al2SiO5 was carried out through an experimental protocol. Initially, a controlled turbid solution was prepared by dispersing 0.5 cm^3 of sieved clay (using a 270 mesh sieve to ensure fine particles) in 1000 ml of distilled water. This standardized preparation method ensures consistency of results and reproducibility of initial turbidity, as shown in Figure (2). The preparation of colloidal solutions with controlled turbidity is a common practice in flocculation and coagulation studies, ensuring comparability of results (Edzwald, 2011; Lipps, Braun-Howland and Baxter, 2012).

To ensure complete disaggregation and dispersion of colloidal clay particles, 1.0 ml of a sodium hydroxide (NaOH) solution, with a concentration of 0.5 molar, was added to the clay suspension, followed by a one-minute stirring and mixing period for material homogenization. This step is fundamental to create a stable colloidal system for the flocculant test (Alves, Borges and Fonceca, 2019). Contextually, NaOH increases the pH of the prepared colloidal solution, intensifying the negative charge on the clay surface in addition to the presence of sodium, increasing its hydrated ionic radius, inducing greater repulsion between particles, ensuring that the clay remains stably dispersed as a colloid, making the flocculant's performance more indicative of its real capacity, making this methodology fundamental for the studies carried out in this article. The use of NaOH to adjust pH and promote the dispersion of colloidal particles is a well-established technique in surface chemistry and water treatment (Snoeyink and Jenkins, 1980).

Quantitatively, using a manual turbidimeter (portable turbidimeter 0-1000 FTU Fast Tracker EPA Ref. HI98703-02), the turbidity of the prepared colloidal solution was analyzed, measuring 1000 NTU (limit of the equipment used), as shown in Figure (3). This process is fundamental to ensure that all tests started from the same turbidity level, in order to guarantee the reliability of the tests in each of the repetitions performed. Furthermore, using a pocket pH meter (Measuring range 0.00-14.00 pH – Accuracy ±0.02 – With Built-in Electrode, Kasvi) an average value of 9.9 was measured for this solution. To summarize the exposed, the actions can be viewed through Table (1). Turbidity and pH measurement are essential parameters for quality control in water treatment studies and are widely used in international standards (ISO 7027; Lipps, Braun-Howland and Baxter, 2012).

4.2. Preparation of test tubes

From the prepared clay solution, 40 ml aliquots of this dispersed solution were deposited into individual capped test tubes for the experimental assays, totaling 20 filled tubes to be used later. A precise quantity of 0.005 grams of residual aluminum silicate, both in its pre-treated and untreated (sieved only) forms, was added to the respective test tubes containing the clay solution. The precise dosing of flocculants is crucial for process optimization and is a standard practice in jar tests and coagulation-flocculation studies (Kawamura, 1991; Liu et al., 2021).

It is worth noting that for the use of residual silicate from Brazilian Lithium Company (CBL), it was subjected to a multi-stage preparation protocol, designed to potentially purify and activate the material. Initially, for all received silicate, disaggregation, oven drying at 70ºC for 72 hours, and sieving through a 270 mesh sieve were performed, making the material with a larger contact surface. Drying and sieving are common preliminary steps in sample preparation for analysis and use in treatment processes, aiming for uniformity and increased surface area (Gaudy and Gaudy, 1980).

Subsequently, the received material, after disaggregation and sieving, underwent sequential washing steps: first with distilled water, then with a 1% hydrochloric acid (HCl) solution, and washing with a 0.5 M NaOH solution, generating three types of treated materials and one untreated material (sieved only). After the silicate preparations (previous washes), a final wash with distilled water was performed on the three treated materials, with the aim of removing excess acid and base. Then, the materials were oven-dried at 70°C for 72 hours, totaling four types of silicate, which can now be actually used in flocculation tests, namely:

- Acid-treated aluminum silicate;
- Base-treated aluminum silicate;
- Aqueous-treated aluminum silicate;

Untreated (sieved only) aluminum silicate;

Table 1 – Summary of Parameters for preparing the clay dispersion solution.

Parameter	Value/Condition
Clay Solution Volume	1 Liter
Clay Volume (270 mesh sieved)	0.5 cm³
NaOH Solution Volume [0.5 M]	1 ml
Initial Stirring (Clay + NaOH)	1 minute
Colloidal Solution Turbidity	1000 NTU
Colloidal Solution Average pH	9.9

Figure 2 – Colloidal clay solution prepared for flocculation tests.

Figure 3 – Determination of initial turbidity (1000 NTU) of the prepared clay solution.

These washing procedures with acidic and basic solutions are often employed to purify and modify the surface of materials, such as silicates, altering their adsorption and flocculation properties (Murray, 2006). Subsequently, continuing the experimental part, to establish a baseline for comparison, control tubes were prepared, including a control (only colloidal solution at 1000 NTU) without silicate addition and a comparison standard using specifically untreated, sieved-only silicate, allowing a direct evaluation of the inherent flocculating efficacy of residual aluminum silicate. This methodology ensured the preparation of 20 test tubes, distributed as follows:

- 4 test tubes with colloidal solution (1000 NTU) + acid-treated Al2SiO5;
- 4 test tubes with colloidal solution (1000 NTU) + base-treated Al2SiO5;
- 4 test tubes with colloidal solution (1000 NTU) + aqueous-treated Al2SiO5;
- 4 test tubes with colloidal solution (1000 NTU) + untreated Al2SiO5 (sieved only);
- 4 test tubes with colloidal solution (1000 NTU) - control;

After adding the aluminum silicates to the tubes, they were subjected to vigorous stirring for 10 seconds to ensure initial mixing and contact between the flocculant (0.005 grams of one of the materials) and the dispersed particles. Subsequently, the tubes were left to rest, allowing the flocculation and decantation processes to occur. This sequence simulates the rapid mixing and subsequent slow mixing/sedimentation phases typical in water treatment plants (Tchobanoglous et al., 2014). Finally, it is essential to understand that four tubes of each material were prepared, each of which will be opened at one-hour intervals. To organize the measurements, they were.

Finally, and explicitly, it is essential to understand that four tubes of each material were prepared, with each one of these being opened at one-hour time intervals. To organize the measurements, they were arranged, as Figure (4) demonstrates, so that the rows will be read, using the turbidimeter, at the mentioned interval, and the columns refer to one of the types of material used.

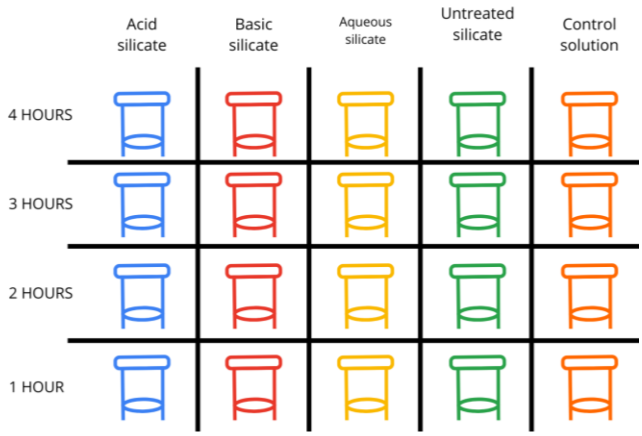

Figure 4 – Preparation and organization of test tubes for the experiment.

The effectiveness of the flocculation process was quantitatively evaluated by measuring the turbidity of the solution using the manual turbidimeter, as previously mentioned. Measurements were taken at defined one-hour intervals, with the maximum test duration extending to four hours. The tests were performed in triplicate for each reading. Practically, turbidity analysis serves as a direct indicator of the concentration of suspended solids and the efficiency of particle aggregation. Measuring turbidity at regular intervals is a common practice to monitor flocculation kinetics and particle removal efficiency (Gregory, 2006).

Figure 5 – Collection and reading of samples, through the experiment of turbidity decay.

Table 2 – Distribution and procedure for preparing test tubes.

Parameter	Value/Condition
Sieve Mesh for Silicate	270 mesh
Drying Duration for Silicate	72 hours
Drying Temperature for Silicate	70°C
Aliquot Volume for Tests	40 ml
Silicate Mass (treated/untreated)	0.005 grams
Stirring Time (after silicate)	10 seconds (strong stirring)
Test tubes needed	20
Rest Periods for Turbidity Measurement	1 hour
Maximum Test Time	4 hours

5. Results and Discussion

5.1. Effectiveness in Particle Aggregation and Turbidity Reduction

After the sequences of laboratory tests, the results obtained in the study demonstrated that the residual aluminum silicate tested acted 'significantly in the aggregation of clay particles dispersed in water.' This observation confirms the potential of Al2SiO5 as a flocculating agent, which could be a candidate for water and sewage treatment plants, since the material acted significantly in the aggregation of clay particles dispersed in an aqueous medium. Furthermore, it is noteworthy that all assays started with a controlled turbidity of 1000 NTU, in accordance with the methodology. Consistent with the presented data, the performance of the residual silicate was superior to the control treatment, which consisted only of the colloidal solution and showed a considerably smaller turbidity reduction.

From a quantitative point of view, Table (3) expresses the average turbidity reduction over time for each type of material, comparing it with the control solution. In addition, for greater data reliability, the Standard Error of the Mean (SEM) was calculated between repetitions, given that the experiment was performed in triplicate.

As shown in Table (3), the tests with aluminum silicate, regardless of the prior treatment (acid, basic, aqueous, or untreated silicate), resulted in a sharp drop in turbidity in the first hour of measurement compared to the control solution. The initial analysis reveals a marked difference in performance between the silicate-based materials and the control solution. In just one hour of rest, the control solution showed a turbidity reduction of approximately 30.4%, dropping to 696.33 ± 72.82 NTU. In contrast, all treatments using residual aluminum silicate achieved a reduction of over 64% in the same period. For example, the average turbidity of the untreated silicate reduced to 277.67 ± 7.62 NTU, while the basic silicate reached 354.67 ± 37.39 NTU, maintaining the pattern over time.

Table 3 – Results of the mean values SEM of turbidity (NTU) obtained from the repetitions of the assay with colloidal solution at one-hour time intervals.

Hydrogen potential (pH) = 9.9				
(NTU) X (h)	1	2	3	4
Acid Silicate	325.67 ± 35.85	185.00 ± 20.60	135.67 ± 10.16	108.20 ± 14.47
Basic Silicate	354.67 ± 37.39	194.33 ± 22.81	144.33 ± 9.44	117.13 ± 20.45
Aqueous Silicate	300.67 ± 23.36	205.00 ± 15.54	131.00 ± 7.78	99.20 ± 9.81
Sieved Silicate	277.67 ± 7.62	180.67 ± 3.41	130.00 ± 9.74	112.00 ± 1.24
Control Solution	696.33 ± 72.82	624 ± 74.37	477.00 ± 29.22	407.00 ± 24.60

After four hours of rest, the average turbidity of the aluminum silicate treatments ranged between 99.20 ± 9.81 NTU (aqueous silicate) and 117.13 ± 20.45 NTU (basic silicate), showing an approximate turbidity reduction of 89.08% compared to the start of the experiment, while the control treatment remained at 407.00 ± 24.60 NTU, reducing by only 59.30%. Therefore, the data confirm the flocculating potential of the study object.

Figure (6), which illustrates the turbidity decay over time, reinforces the effectiveness of residual Al2SiO5 as a particle aggregator, illustrating the kinetic behavior of the flocculation process. The curves of all treatments with aluminum silicate reveal a sharp reduction in turbidity in the first hour, suggesting an initial stage of rapid coagulation and flocculation, followed by a more gradual decantation process in the subsequent hours. Such behavior contrasts sharply with that of the control solution, whose curve shows a much slower and less expressive decrease in turbidity. The kinetics of flocculation and sedimentation is a crucial aspect in the evaluation of flocculants, and the observation of a rapid initial phase followed by a slower one is consistent with the literature (Gregory, 2006).

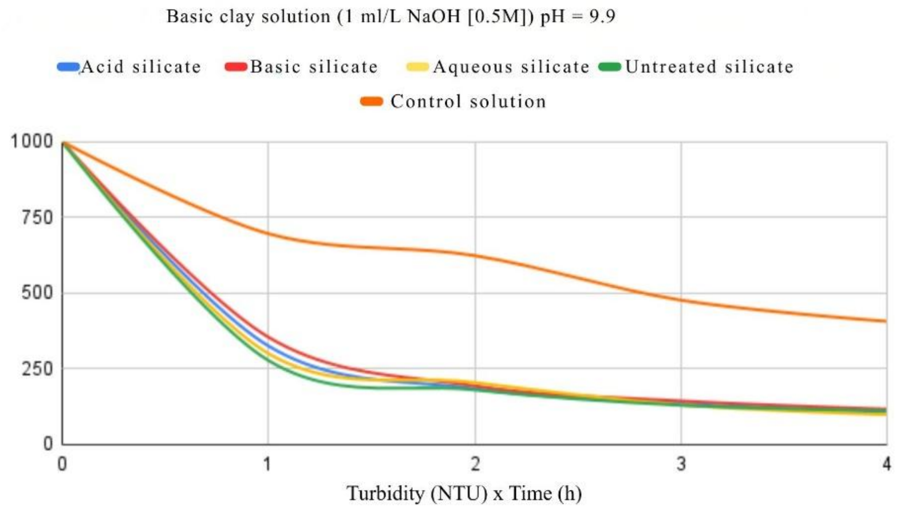

Figure 6 – Turbidity Decay.

From a critical perspective, the analysis of variance, detailed in Figure (7) through the bar graphs, provides statistical support for the effectiveness of the studied material. The results show that the difference in turbidity between the silicate treatments and the control solution was statistically significant at all measurement points ($p<0.05$), for the first, second, third, and fourth hours of the test. This statistical confirmation is crucial, as it validates the conclusion that the reduction in turbidity is a direct and unequivocal result of applying residual aluminum silicate.

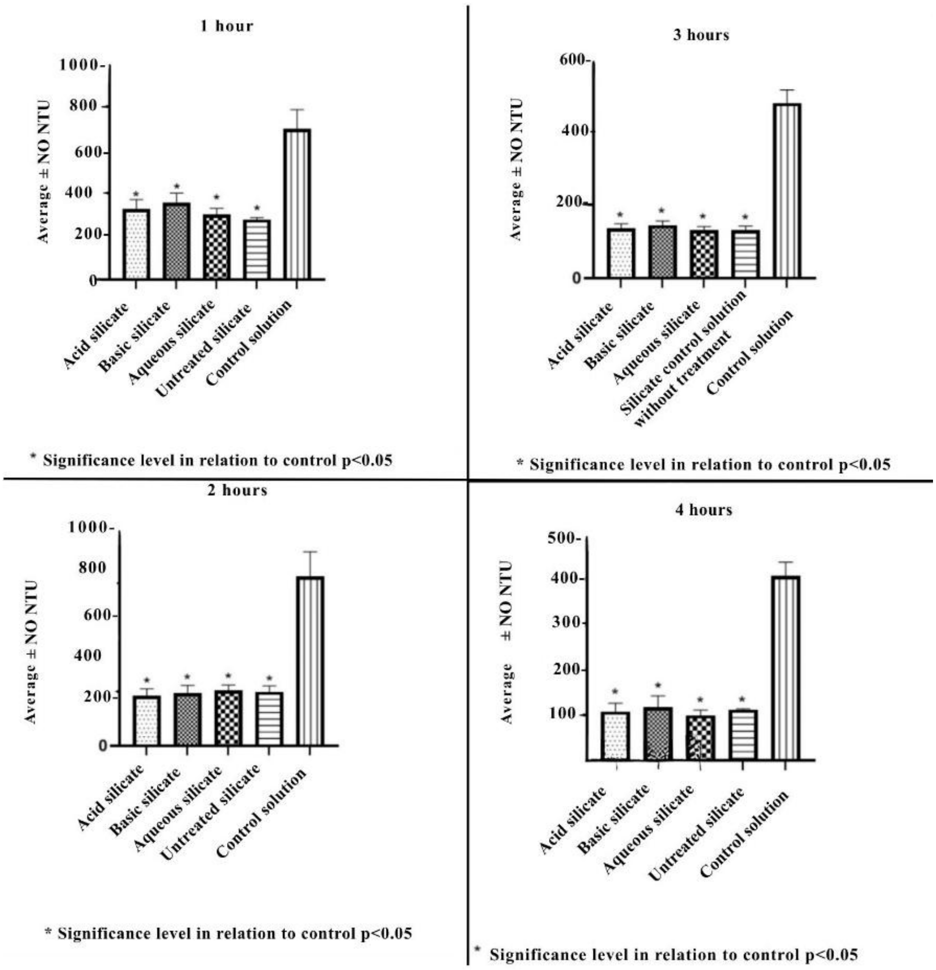

Figure 7 – Results obtained in this study of turbidity concentration (NTU) at different times (h), using a basic colloidal clay solution (1 ml/L of NaOH [0.5M]) pH = 9.9).

5.2. Flocculant Action Mechanism and pH Influence

The study results confirmed that the residual aluminum silicate showed greater efficiency in alkaline conditions, with an initial average pH of 9.9 in the colloidal solution. The pH dependence suggests that the flocculation mechanism may involve charge neutralization and/or sweep flocculation, where aluminum hydrolysis products form precipitates that trap dispersed particles (Alves, Borges and Fonceca, 2019). Still following the logic of the authors mentioned above, it is fundamental to mention that pH optimization is a crucial factor for flocculant performance, and in many cases, alkaline conditions favor process efficiency. Furthermore, understanding the aluminum species formed at high pH is fundamental to optimize performance and predict the material's behavior in different water matrices. Studies on the chemistry of aluminum in aqueous solutions and its influence on flocculation are widely documented (Stumm and Morgan, 1995).

It is important to note that the treatments performed with water, acid, or base did not promote significant changes in the silicate's behavior in the clay flocculation process. The turbidity analyses did not distinguish between the materials, showing a behavior similar to the use of untreated residual aluminum silicate, only disaggregated and sieved. This suggests that the simple separation of the residual silicate particles by sieving was sufficient to confer good performance to the process, not requiring more chemical treatments for the use of the residual material.

5.3. Limitations and Practical Implications

Despite the exceptional flocculating performance of the residual aluminum silicate, a critical limitation was identified in the study: the material was not able to reduce turbidity to levels below 50 NTU. The minimum turbidity values achieved, even after four hours, remained above 99 NTU. This limitation indicates that, in its current form, the material does not meet the turbidity standards for drinking water, which generally require values below 5 NTU, as established by Ordinance GM/MS No. 888 of 2021 of the Ministry of Health (Brazil, 2021).

However, it is worth noting that this limitation does not devalue the material, but, on the contrary, directs its application to a context of greater impact and viability. The residual aluminum silicate should not be considered a final stage flocculant, but rather a highly effective pre-treatment agent. The ability to reduce turbidity from 1000 NTU to approximately 100 NTU, a 90% reduction, is an extraordinary result for the treatment of effluents with a high load of suspended solids. This perspective repositions the material as a strategic resource for the management of industrial effluents. For example, in mining operations, the residual silicate could be applied directly for the clarification of mining effluents or in settling basins.

This initial application could drastically reduce the solids load, facilitating and cheapening the subsequent treatment steps. Consequently, by transforming a waste from an industrial process (lithium mining) into a solution for an environmental problem in the same sector, the study proposes a closed and high-value circular economy model, with direct and positive economic and environmental implications for Brazilian Lithium Company (CBL) itself (Stem et al., 2025; Magalhães, Silva and Peres, 2022).

6. Final Considerations

The present study successfully demonstrated the potential of residual aluminum silicate (Al2SiO5), from the processing of lithium by CBL, as an effective flocculant to flocculate clay particles. The results revealed its superior capacity compared to the control solution (colloidal solution at 1000 NTU) and its effectiveness in basic pH environments (pH ≈ 10) in all tested aluminum silicate preparations. This research not only validates a new application for a mining by-product, but also exemplifies the principles of the circular economy, transforming waste into a valuable resource for sustainable water treatment, acting as an artificial zeolite that can be used in the mining sector itself.

However, despite the promising results, the identified limitation of low electrical charges prevents the reduction of turbidity to levels below 50 NTU, indicating that, in its current form, the material is more suitable for pre-treatment or as part of a multi-stage treatment system to achieve more stringent potability standards. However, this limitation serves as a clear starting point for future investigations and new types of treatment on the residual material. Thus, the optimization of the material's properties, the elucidation of its action mechanisms, and the exploration of its applicability to a wider range of contaminants and on a larger scale are the next essential steps of studies, paving the way for new branches of research in the area. Thus, it is worth highlighting mainly studies that focus on opening the material's charges.

In short, the valorization of waste from these exploratory activities, such as residual aluminum silicate, represents a promising frontier in environmental and water engineering, in addition to quality improvement. Therefore, by transforming waste challenges into innovative solutions for water management, this research contributes to the construction of a more sustainable and resilient mining industrial scenario, where resource efficiency and environmental protection go hand in hand, leading to the valorization of waste from industry and mining.

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