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ORIGINAL STUDY

The Effect of Chemical Coagulant Dosages on the Removal of Turbidity from Wastewater

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ABSTRACT

This research aims to compare different coagulants, which are alum, ferric chloride, and polyaluminum chloride, in treating turbidity in water. The objective is to determine the optimal dosage of each coagulant for the removal of visible turbidity at levels of 400, 85, 70, and 40 NTU, respectively. The study also considers the (pH) levels resulting from the addition of coagulants, measures the percentage of remaining materials from the used coagulant (sulfates from alum, chloride from ferric chloride, and chlorides from polyaluminum chloride). A 1000 L tank and its components were controlled by adding the desired pollutants (clay and plant impurities) and known, Oxygen Demand (BOD), 20 mg/L. The experimental results demonstrate that ferric chloride has an advantage in turbidity removal, especially when the standard turbidity value is 5 NTU. The optimal dosage is found to be 23 mg/L for 400 NTU, 20 mg/L for 85 NTU, 17 mg/L for 70 NTU, and 10 mg/L for 40 NTU. Therefore, the results of pH were improved from 7.0 to 7.8, as well as ferric chloride from 12 to 17 mg/L for poly aluminum chloride. The study reveals a significant increase in chloride ions with the addition of ferric chloride and polyaluminum chloride, while there is a slight increase in sulfate ions with the addition of alum.

Keywords: Drinking water safety, Water treatment, Turbidity, Ferric chloride, Chemical coagulants

1. Introduction

In 2017, the World Health Organization (WHO) highlighted that over 2.1 billion individuals, constituting nearly a third of the global population, lacked access to safe drinking water free from various forms of physical, chemical, and microbial contaminations [1–3]. According to the World Health Organization (WHO), approximately 1.8 million deaths are attributed to diarrheal diseases annually, primarily resulting from the ingestion of contaminated drinking water [4, 5]. Individuals with compromised immune systems due to chronic conditions like diabetes, cancer, and AIDS, among others, as well as young children and the elderly, are especially susceptible to waterborne infections [6]. In the relentless pursuit of ensuring the availability of clean and potable water, the selection of appropriate water treatment coagulants becomes a pivotal aspect of the process [7]. Among these coagulants, ferric chloride stands out as a noteworthy candidate, prompting an in-depth investigation into its suitability for water treatment applications [8]. This comprehensive evaluation delves into various facets of ferric chloride's performance, cost-effectiveness, and potential impacts on the environment and human health [9].

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Water treatment plants play a critical role in purifying water for consumption, addressing challenges posed by colloidal particles and suspended matter that often elude conventional settling basins at standard flow rates [10]. Consequently, a multi-staged treatment approach, incorporating processes like sedimentation and coagulation, becomes imperative. In this context, the introduction of chemical substances, such as ferric chloride, facilitates the alteration of the physical state of suspended and colloidal particles, optimizing their removal [11]. The efficacy of any water treatment coagulant is contingent upon its performance, cost implications, and the broader ramifications on environmental and human health. Ferric chloride's role in this intricate balance becomes the focal point of scrutiny, aiming to uncover its efficiency in mitigating water impurities, its economic feasibility concerning cost-effectiveness, and the potential ecological and health repercussions associated with its usage [12]. As we embark on this exploration, the evaluation encompasses an array of considerations. The performance aspect scrutinizes the ability of ferric chloride to effectively coalesce and remove turbidity, particularly when compared to other conventional coagulants like aluminum sulfate (alum) and poly aluminum chloride (PACL). Simultaneously, the economic viability of ferric chloride is under the lens, assessing its cost-effectiveness concerning the dosage quantities required for optimal results. Moreover, recognizing that the deployment of coagulants inherently introduces chemical substances into the water supply, the study diligently investigates the potential environmental and health impacts. This involves a meticulous examination of residues left behind by ferric chloride, including the presence of aluminum ions and other elements, along with an analysis of alterations in water acidity [13].

Water treatment for drinking purposes occurs at water treatment plants, where a significant portion of colloidal particles and suspended matter in the water is often so small that it is difficult or impossible to remove at designed and normal flow rates in settling basins [14]. Therefore, treatment is carried out in multiple stages, including sedimentation and coagulation, with the addition of certain chemical substances that assist and enhance the sedimentation process [15–18]. These chemicals alter the physical state of suspended, colloidal, and dissolved solid materials, facilitating their disposal [18, 19]. The use of different chemicals (coagulants) requires knowledge of their specifications and determining the suitable and optimal operating conditions to achieve the lowest effective concentration of the coagulant substance, thus reducing costs and improving efficiency [20]. Additionally, the study investigates the residues of the used chemicals, such as aluminum ions, iron, and sulfates. Some studies have indicated the presence of residual effects of aluminum, iron, and sulfates when using different concentrations of alum or other substances [21, 22]. The primary goal of the coagulation and flocculation process is the removal of visible turbidity from water [23, 24]. (Turbidity) is the cloudy appearance of water caused by small particles dispersed in it [25, 26]. The coagulation and flocculation process involves several stages, starting with rapid mixing after adding the required coagulant [27]. The purpose of this step is to evenly and quickly distribute the chemical substance (coagulant) in the water, considering the required mixing time, which is one minute (60 sec) [28]. If the time is less than a minute, it leads to uneven distribution of the substance, and if it exceeds the required time, it may cause the breakage of small primary flocs into smaller ones, affecting subsequent processes. The coagulation process begins after rapid mixing, where the coagulant neutralizes the electrical charge of small and colloidal particles in the water, allowing them to approach each other and form larger particles [29]. Three materials were selected for experimentation: Aluminum sulfate (alum) $Al_2(SO_4)_3.18H_2O$, Ferric chloride $FeCl_3.6H_2O$, and Poly aluminum chloride (PACL) $Al_2(OH)_3Cl_3$. Alum will serve as a comparative material in various aspects, including cost, dosage quantity, and performance efficiency [21, 23]. The goal of the research paper is to conduct a thorough examination and analysis of ferric chloride as a coagulant in water treatment processes. The evaluation aims to assess various aspects, including the coagulant's efficiency in water treatment (performance), its economic viability (cost-effectiveness), and its possible effects on the environment and human health. The overarching objective is to provide a comprehensive understanding of the implications and benefits of using ferric chloride in water treatment applications.

2. Materials and methods

The work in this research is carried out through several stages. Three materials were selected for experimentation: Aluminum sulfate (alum) $Al_2(SO_4)_3.18H_2O$, Ferric chloride $FeCl_3.6H_2O$, and Poly aluminum chloride (PACL) $Al_2(OH)_3Cl_3$. Alum will serve as a comparative material in various aspects, including cost, dosage quantity, and performance efficiency.

1. Preparation of the primary tank: control the turbidity and concentrations of substances in it to obtain a stable source for the experiments. The

Fig. 1. Schematic diagram for the jar test device.

water concentrations for each model are drawn for experimental purposes. The tank is made of cylindrical polyethylene (PE) with a capacity of 1000 L, equipped with an electric mixer to ensure the uniformity of its contents.

2. Jar test device: use the Wise stir (Jar test) device (model JT m6) from DAIHAN Scientific, a Korean company. This device is used to compare the performance results of coagulants and determine the appropriate dosage.
3. Measurement of turbidity: use the WTW Turb 550 device for each model to read and measure turbidity, determining the optimal dosage.
4. Analysis of ion concentrations: Ion concentrations are analyzed before and after the addition of coagulants (Al^{+3}, $SO_4{}^{-1}$, Fe^{+3}, Cl^{-1}) by the water research center. The following chemicals are used:
    1. Aluminum Sulfate (alum): $Al_2(SO_4)_3.18H_2O$
    2. Ferric Chloride: $FeCl_3.6H_2O$
    3. Poly Aluminum Chloride (PAC): $Al_2(OH)_3Cl_3$.

The comparison between them and the required analyses involve preparing a standard solution for each of them and adding it to the model in varying quantities for six batch models, namely 0, 5, 10, 20, 30, and 40 mg/L. The experiments are conducted using a (jar test) device, automatically set to fast mixing for one minute with 300 revolutions per min. Subsequently, it switches to slow mixing at 30 revolutions per minute for ten minutes, followed by a 15-min waiting period to allow for sedimentation. Readings are then taken, including turbidity and acidity measurements, and samples are collected for the required analyses.

2.1. Methodology

1. A 1000 L tank equipped with an electric mixer for homogenizing its contents. Its components are controlled by adding the desired pollutants (clay and plant impurities) and known values for Biological Oxygen Demand (BOD), which were measured and found to be 20 mg/L.
2. Jartester jar test device for six batch models (see Fig. 1).
3. Portable pH meter of type HAANA HI 8314 for measuring acidity.
4. BOD measurement device of type oxi Top with a dark bottle.
5. Sartorius BL 210 S precision balance.
6. Portable electronic thermometer of type HANNA HI 8314.

The final stage is flocculation, where slow and gentle mixing helps the flocs formed in the previous stage come into contact, aggregate, and coalesce before settling (see Fig. 2).

3. Results and discussions

3.1. The effect of coagulant dosages on turbidity

It has been tested and examined for 72 models, with water turbidities of 400, 85, 70, and 40 NTU [31]. This was done with six batch models for each turbidity measurement, using three selected

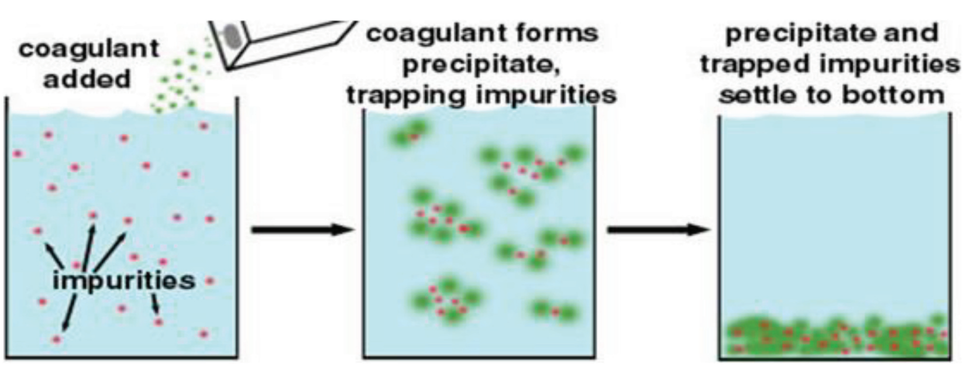

Fig. 2. Illustrates the stages of the clotting and agglutination process.

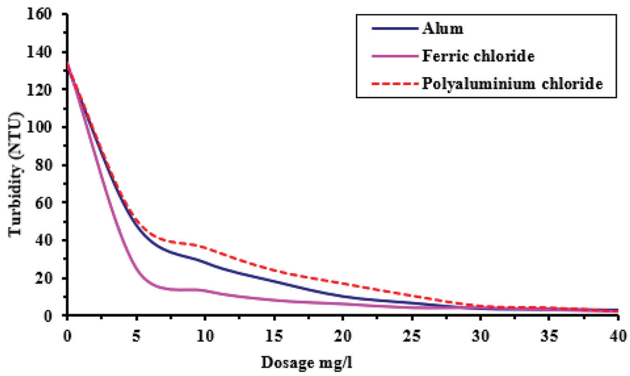

Fig. 3. Dosage vs turbidity relationship for (400 NTU) sample, (alum), (FC), and (PAC).

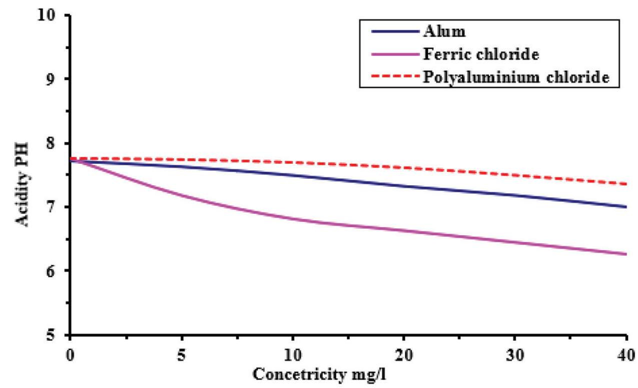

Fig. 4. Concentration of coagulants vs pH for (400 NTU) sample (alum), (FC), and (PAC).

coagulants: aluminum sulfate (alum), ferric chloride, and poly aluminum chloride (PAC) [32]. The economic viability of ferric chloride assessed its cost-effectiveness concerning the dosage quantities required for optimal results. Different dosages were applied, namely 0, 5, 10, 20, 30, and 40 mg/L [33]. The results are depicted in the attached graphs below:

Fig. 3 shows, it is evident that the most effective substance in removing primary turbidity measured at 400 NTU was ferric chloride, particularly at a dosage of 23 mg/L. In contrast, the equivalent dosage for alum was around 28 mg/L, and for poly aluminum chloride, it was approximately 33 mg/L [34]. However, it is notable that the impact of ferric chloride on turbidity is rapid and yields good results. At a dosage of 5 mg/L, the turbidity value was 25 NTU, while for alum, it was approximately 17 mg/L, about three times lower.

3.2. The effect of coagulant dosages on pH

Fig. 4 shows, where the acidity of water was monitored and measured after adding the coagulant, it is observed that the water becomes acidic after adding ferric chloride, reaching below pH 7.0 [35]. This suggests that the aqueous solution of ferric chloride is more acidic, leading to the consumption of the alkalinity present in the water, forming ferric hydroxide ($Fe(OH)_3$) [36]. In contrast, the acidity of the water remained basic (around pH 7.0) after adding alum [37]. The dissolution of alum in water forms sulfuric acid as a side reaction, which, in turn, reacts with bicarbonates to produce carbon dioxide gas [38]. This gas reacts with water to form carbonic acid, causing a decrease in pH. As for poly aluminum chloride, the change in acidity was minimal, not exceeding 0.7 units, and stabilized at pH 7.8 [39]. This is attributed to the basic nature of poly aluminum chloride.

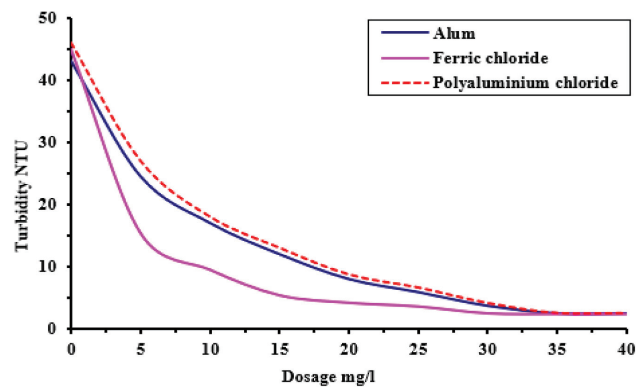

Fig. 5. Dosage vs turbidity for (85 NTU) sample (alum), (FC), and (PAC).

Fig. 5 shows, where the experiment was repeated for water samples with a lower turbidity concentration of 85 NTU, obtained by allowing the settling of the primary raw water (400 NTU) for a period of time, it is evident that most of the relatively larger particles have settled [40]. This condition also favored ferric chloride, and at a concentration of 22 mg/L, it outperformed alum and poly aluminum chloride, whose equivalent dosages were 30 mg/L for each. Additionally, the rapid impact of ferric chloride on turbidity is noticeable at lower dosages. At a dosage of 5 mg/L, the turbidity was measured at 15 NTU [40].

Fig. 6 shows, where the acidity of the low turbidity water sample (85 NTU) was measured, it is also observed that ferric chloride exhibits an acidic trend, reaching below pH 7 [41]. Similarly, alum shows an acidic trend but remains within basic limits. Poly aluminum chloride also exhibits a narrow range within the basic pH, as noted in the graph.

Fig. 7 shows, a convergence of results is observed for the three coagulants in the water model with a turbidity of 70 NTU [42]. This turbidity level was obtained by allowing the settling of the standard

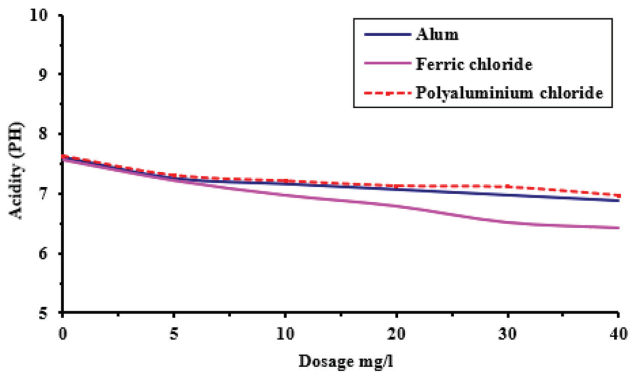

Fig. 6. Dosage vs acidity of (85 NTU) sample (alum), (FC), and (PAC).

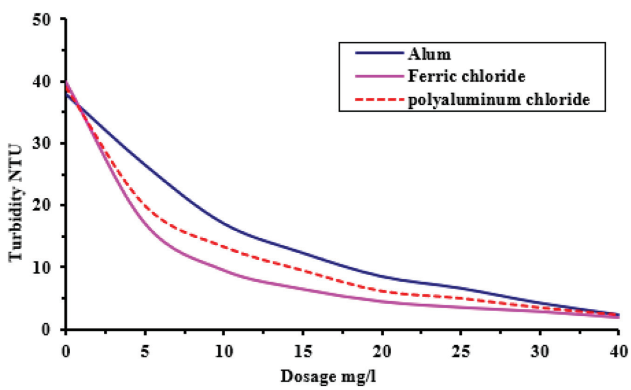

Fig. 7. Dosage vs turbidity of (70 NTU) sample (alum), (FC), and (PAC).

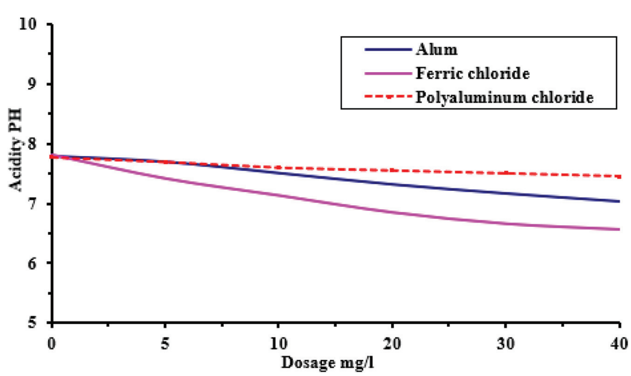

Fig. 8. Dosage vs acidity of (70 NTU) sample (alum), (FC), and (PAC).

sample (400 NTU) for a longer period, resulting in the settling of most of the relatively larger particles. An improvement in the performance of the coagulants is evident at lower turbidity concentrations for both alum and poly aluminum chloride.

Fig. 8 shows the observation of the acidity readings, it is evident that the slope of the readings does not differ from the previous ones. This can be attributed to the acidic nature of both ferric chloride and alum,

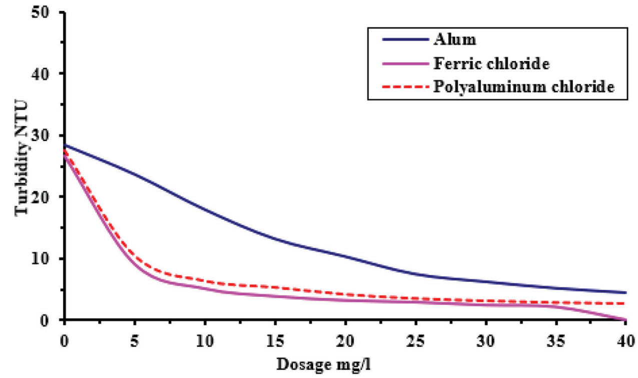

Fig. 9. Dosage vs turbidity of (40 NTU) sample (alum), (FC), and (PAC).

which is a natural occurrence [43]. As the dosage increases, the acidity tends to increase. In contrast, poly aluminum chloride is characterized by its alkaline nature and has a lesser impact on the acidity of the water.

Fig. 9 shows the water model with a turbidity of 40 NTU, obtained by allowing the settling of the standard sample for a long period and then diluting it with clear water to achieve the desired turbidity, a significant convergence is observed for both poly aluminum chloride and ferric chloride compared to alum at a dosage of 5 mg/L [44]. The performance of poly aluminum chloride has greatly improved at lower turbidity levels, and the best turbidity reading was 5 NTU at a dosage of 12 mg/L for ferric chloride and 17 mg/L for poly aluminum chloride. At 40 mg/L, alum showed the highest turbidity, especially at the standard turbidity level.

Fig. 10 shows the acidity readings remain consistent with the previous observations, with ferric chloride exhibiting higher acidity than alum, while poly aluminum chloride retains its alkaline behavior. Ion analyses were conducted for sulfates in the case of alum and chlorides for both poly aluminum chloride

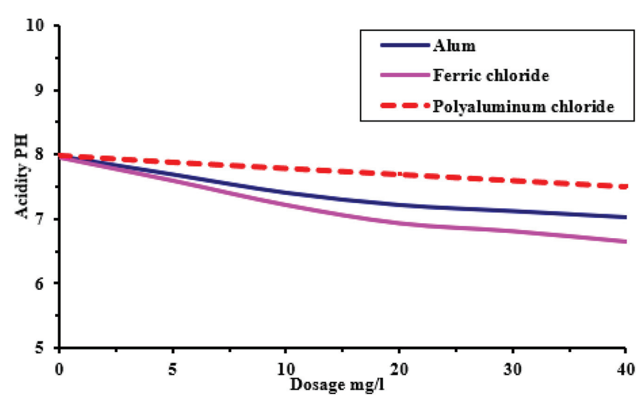

Fig. 10. Dosage vs acidity of (40 NTU) sample (alum), (FC), and (PAC).

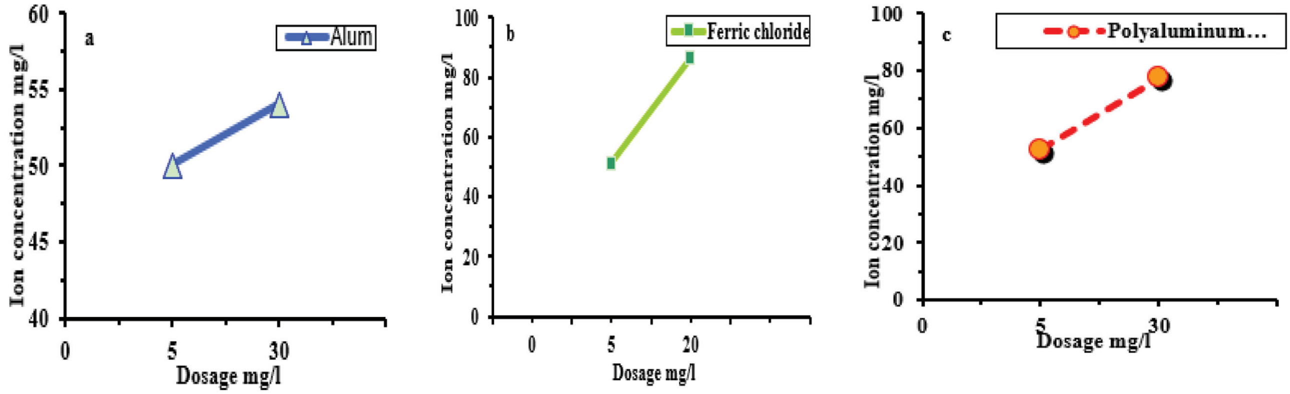

Fig. 11. (a) Dosage vs concentration of the sulfate ion of alum SO_4, (b) Dosage vs chlorine ion concentration in ferric chloride, (c) Dosage vs concentration of chlorine ions.

and ferric chloride. Two samples were taken for each experiment due to the inability of the water research center to analyze a large number of samples. It was also challenging to conduct aluminum ion analyses. Water samples were taken at a turbidity of 70 NTU for only two readings due to limitations in analysis capabilities. One sample represented the lowest added dosage (5 mg/L), and the other was taken at the ideal dosage, close to the turbidity level of 5 NTU, specifically at 20 or 30 mg/L.

Fig. 11 (a, b, and c) shows the observation an increase in concentrations is evident due to the addition of coagulants. It is noticed that the increased ratio for sulfate ions upon adding alum is low (4 mg/L), which may be attributed to the reaction of sulfates with calcium ions forming insoluble calcium sulfate. While most chlorides are soluble salts, they are observed in the analysis results after adding coagulants containing chlorides, and the increase in ion concentrations remains within the allowable limits according to the World Health Organization (WHO) specifications (4). An increase in chloride concentrations is an indicator of increased iron concentration resulting from the use of ferric chloride as a coagulant, and aluminum from the use of polyaluminum chloride. Additionally, an increase in sulfate concentrations is an indicator of aluminum from the use of alum, as measurements for iron and aluminum elements were hindered due to the lack of necessary materials at that time. The above results (Figs. 3, 5, 7 and 9) demonstrate the effectiveness of ferric chloride in removing turbidity up to 5 NTU for all tested turbidity levels (400, 85, 70, 40). Some sources indicate the superiority of polyaluminum chloride, especially in color removal and low turbidity levels. While this is true when compared to alum, in the current research, polyaluminum chloride did not exhibit the same advantage when compared to ferric chloride. There is a significant similarity between ferric chloride and polyaluminum chloride in the experiment with turbidity of 40 NTU, and its performance may improve at values lower than that. Also, the measurement of water acidity (Figs. 4, 6, 8 and 10) reveals the acidic nature of coagulants. As the dose increases, the acidity (pH) decreases for both alum and ferric chloride, except for polyaluminum chloride, which maintains an alkaline environment. Further research is required to understand the impact of drinking water on these treatments and analyses.

The nature of the raw water used in the experiment may have influenced the lack of superiority of polyaluminum chloride. Regular tap water was used, pre-treated with alum, and added with a quantity of local clay soil to obtain the desired turbidity. This affected the pH level for the water model, in addition to the quality of impurities, as they were relatively large clay particles and dissolved salts. Large particles may have caused inconsistent turbidity readings as they settled due to their weight, not due to the effect of the coagulant. It is evident that the effective dose in all experiments is within the range of 20 and 30 mg/L except for the last experiment with 40 NTU, where the optimal dose was 10 mg/L for ferric chloride, 17 mg/L for polyaluminum chloride, and 40 mg/L for alum. The high dose for alum may be due to its inability to contain fine particles within the available time period. Ion analysis measurements require further study, as the number of models was limited, and they serve as indicative readings. It was clear that using polyaluminum chloride and ferric chloride led to a significant increase in soluble chlorides, while using alum led to a slight increase in sulfate ions [45]. A comparison with standard drinking water specifications and allowable salt levels is needed, which is 250 mg/L for chlorides and 250 mg/L for sulfates according to the World Health Organization (4).

4. Conclusions

Performance of Coagulants: Ferric chloride demonstrates superior performance in turbidity removal compared to polyaluminum chloride and alum. Ferric chloride achieves effectiveness up to twice as much as other coagulants when used at low doses. Cost of Coagulants: Ferric chloride proves effective in performance and stands out as the most economical choice when comparing prices and used doses. This economic advantage is attributed to the local availability of ferric chloride due to local manufacturing. Environmental and Health Studies: Conduct comprehensive environmental studies to assess the impact of ferric chloride usage on the environment. Perform a health assessment for the coagulant and its impact on the resulting water quality. Practical Studies: The practical use of ferric chloride as a new coagulant requires an in-depth analysis of infrastructure needs and integration with existing processes. Sustainability: Study the impact of coagulants on sustainability, including resource and energy consumption. Water Technology: Explore modern and advanced water treatment technologies for comparison with traditional coagulants. Quality Control: Implement quality control procedures to monitor the impact of coagulants on drinking water. Collaboration with Local Industry: Encourage collaboration with local industries to achieve economic sustainability and enhance local supply capacity.

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