

Research Article

A Comparative Study of Pre-hydrolysed Coagulants and Alum in Surface Water Clarification

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Abstract

The aim of the present study was to evaluate the performance of two pre-hydrolyzed aluminum coagulants (PAX-XL6 and PAX-XL8) in comparison with aluminum sulfate (alum) for surface water clarification. Jar-test experiments were conducted with coagulant doses ranging from 0 to 15 mg Al/L to determine the optimal dose. Results demonstrated that both the coagulant type and dosage strongly influenced clarification performance. The pre-hydrolyzed coagulants achieved the best results, with maximum color removal efficiencies of 91.8% and turbidity removals of 89.3% (PAX-XL6) and 84.6% (PAX-XL8) at an optimal coagulant dose of 4 mg Al/L. In contrast, alum showed the lowest clarification performance, achieving maximum color removal of 87.5% and turbidity removal of 80.3%. At 4 mg Al/L, the pre-hydrolyzed coagulants met WHO drinking water guidelines for color and turbidity, whereas alum failed to meet color standard. Beyond 8 mg Al/L, all coagulants exhibited a decrease in clarification efficiency due to colloid restabilization. Regarding water chemistry, PAX-XL6 and PAX-XL8 induced only moderate reductions in pH and alkalinity, whereas alum caused significant acidification and a marked decrease in alkalinity. None of the coagulants affected water hardness. Overall, the pre-hydrolyzed coagulants demonstrated superior clarification performance and reduced chemical impact, confirming their potential as efficient and sustainable alternatives to alum for surface water treatment.

Keywords

Pre-hydrolyzed Coagulants, Aluminum Sulfate (alum), Coagulation, Clarification, Color Removal, Turbidity Removal, Drinking Water, Surface Water Treatment

1. Introduction

Safe drinking water is essential for human health and sustainable development. To produce drinking water, both surface and groundwater sources are used. However, surface waters are often vulnerable to contamination by organic matter, suspended solids, and colored compounds, which compromise water quality.

Various methods are used to produce safe drinking water. Among them, coagulation - flocculation is one of the most widely used techniques in surface water purification. This process enables the destabilization and aggregation of both hydrophobic and hydrophilic colloidal particles for subsequent removal [1-5]. Its performance strongly depends on

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coagulant type, dosage, and water chemistry parameters such as pH, alkalinity, and hardness [5-9].

Conventional coagulants, such as aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$), aluminum chloride (AlCl_3), ferric sulfate ($\text{Fe}_2(\text{SO}_4)_3$), and ferric chloride (FeCl_3) are extensively used in drinking water treatment [10-13]. Despite their low cost and wide availability, these coagulants present several drawbacks, including significant acidification of treated water, high alkalinity consumption, and the generation of aluminum residues that may pose environmental and health concerns [14, 15]. Their use often requires post-treatment pH adjustments, which increase operational costs and complicate application in some small-scale treatment plants with limited resources and technical staff.

In recent years, pre-hydrolyzed coagulants have been increasingly adopted as attractive alternatives to conventional coagulants. These coagulants generate polymeric aluminum species with high positive surface charge, enabling more effective destabilization of negatively charged particles. Their hydrolysis products also exhibit structural differences compared with those formed by conventional coagulants [16].

Numerous studies have demonstrated the advantages of pre-hydrolyzed coagulants, including enhanced clarification

performance and reduced impacts on pH and alkalinity [5, 17-20].

The objective of this study was to evaluate the performance of two pre-hydrolyzed aluminum coagulants (PAX-XL6 and PAX-XL8) by comparing them with a conventional coagulant (alum) for the clarification of surface water.

2. Materials and Methods

2.1. Chemicals and Reagents

The characteristics of the coagulants used in this study are presented in Table 1. The coagulants were supplied by Kemira Water Solutions Inc. (Atlanta, USA), while the reagents were obtained from Millipore Sigma Canada Ltd. (Ontario, Canada) and Hach Canada (Ontario, Canada). All reagents used for analyses were analytical grade and of the highest purity available. To facilitate their use, stock solutions were prepared at concentration of 1 g Al/L by diluting the commercial solutions with distilled water.

Table 1. Characteristics of stock coagulants solutions.

Coagulant	Concentration of stock solution (g Al/L)
ALS (Aluminum Sulfate - alum)	57.6
PAX-XL6 (Poly-aluminum Chloride 6)	66.4
PAX-XL8 (Poly-aluminum Chloride 8)	68.2

2.2. Sampling

The raw water used in this study was collected in a lake located in Racine (Quebec, Canada). A total volume of 20 L of water was sampled during each campaign using a clean plastic container and stored at 4 °C until use in the experiments. Prior to each experiment, the samples were allowed to reach room temperature (20 - 23 °C).

2.3. Coagulation Experiments

Coagulation experiments were carried out in 1 L beakers using a six-position Jar-test apparatus (Philipps & Bird, USA). Different concentrations of each coagulant (0, 2, 4, 6, 8, 10 and 15 mg Al/L) were added to the raw water samples. The mixtures were subjected to rapid mixing at 200 rpm for 1 min, followed by slow mixing at 40 rpm for 20 min. No flocculant aid was added during the tests. After mixing, samples were allowed to settle for 30 min, and the supernatant was withdrawn for analysis. All experiments were carried out at room

temperature (20 - 23 °C).

2.4. Analytical Methods

2.4.1. pH, Conductivity, and Turbidity Measurements

The pH of water was measured using a pH meter (Acumet excel XL2 pH meter/Ion meter, model S/N XL 94005507, Fisher Scientific Co.) equipped with a Cole-Palmer double-junction electrode (Ag/AgCl reference). A thermometer was used for temperature measurement. Electrical conductivity was measured using a Hach HQ1140 conductivity meter equipped with a 4-pole graphite electrode and an integrated temperature sensor. Turbidity was measured using a Hach 2100Q turbidimeter. pH and conductivity were measured immediately on site after sampling.

2.4.2. Color, Alkalinity, and Water Hardness Analyses

Water color was analyzed by UV-vis spectrophotometry at

400 nm, using a series of standards containing potassium chloroplatinate and cobalt chloride in acidic medium [21]. Water alkalinity was determined by sulfuric acid titration following the CEAEQ method MA.315-Alc-Aci1.0, Rev. 3 [21], and expressed in mg CaCO₃/L. Water hardness was measured by complexometric titration with EDTA (ethylenediaminetetraacetic acid) solution, which chelates Ca²⁺ and Mg²⁺ ions to form Mg-EDTA and Ca-EDTA complexes.

3. Results and Discussion

3.1. Physicochemical Composition of the Raw Water

The physicochemical composition of the raw water is presented in Table 2. The average pH value (5.57) was below the WHO recommended range for drinking water (6.5-8.5) [22]. The average color and turbidity values were 171.5 Pt-Co and 7.81 NTU, respectively, both exceeding the WHO standards for drinking water [22]. Alkalinity and water hardness were approximately 32 mg CaCO₃/L and 29 mg CaCO₃/L, respectively. Water alkalinity contributes to buffering pH and promoting aluminum precipitation, whereas hardness facilitates floc formation during coagulation. Based on the measured hardness, the raw water was classified as “very soft”.

Table 2. Physicochemical composition of raw water.

Parameter	Raw water	WHO standards *
pH	5.62 - 5.97	6.5 < pH < 8.5
Turbidity (NTU)	7.81	< 5
Color (Pt-Co)	171.5	< 15
Alkalinity (mg CaCO ₃ /L)	32	-
Water hardness (mg CaCO ₃ /L)	29	-

*[22]

3.2. Clarification Performances

Clarification performance was assessed through color and turbidity removal as a function of coagulant dose. The optimal dose for each coagulant was determined to minimize operational costs and sludge production, while maximizing treatment efficiency [23, 24].

3.2.1. Color Removal

Figure 1 shows the evolution of color removal as a function of coagulant dosage. For the pre-hydrolyzed coagulants, three distinct performance phase were observed: i) Increasing phase:

characterized by a steady increase in color removal, reaching a maximum of 91.8% at 4 mg Al/L; ii) Pseudo-steady-state phase: characterized by relatively stable color removal (91.8-94.7% for PAX-XL6 and 91.8 - 98.1% for PAX-XL8) as doses increased from 4 to 8 mg Al/L, iii) Decreasing phase: characterized by gradual decrease of the color removal, from 94.7% to 40.8% for PAX-XL6 and from 98.1% to 55.4% for PAX-XL8, as doses exceeded 8 mg Al/L. This decline was due to colloids restabilization caused by the excess of positive charges provided by the flocs [24-27]. This phenomenon led to the destabilization of the coagulation process [5].

The optimal coagulant dose for maximum color removal was 4 mg Al/L. At this dosage, the treated water met the WHO color standard (< 15 Pt-Co).

For Alum, two main phases were observed: i) Increasing phase: characterized by a steady increase in color removal, reaching a maximum of 87.5% at 4 mg Al/L; ii) Pseudo-steady-state phase, observed at doses beyond 4 mg Al/L and characterized by slight decrease in color removal (from 87.5 to 81.6%). Thus, increasing alum doses above 4 mg Al/L did not enhance color removal.

The optimal coagulant dose for maximum color removal with alum was also 4 mg Al/L. At this coagulant dose, the pre-hydrolyzed coagulants successfully met WHO drinking water standards for color (< 15 UCA), whereas alum did not. Water quality at the optimal coagulant dose is presented in Table 3. Based on color removal efficiency, the coagulants ranked as follows: PAX - XL6 > PAX - XL8 > Alum. These results are consistent with Nowacka [5], who reported higher color removal efficiency for pre-hydrolyzed aluminum coagulants such as polyaluminum chloride and aluminum chlorohydrate compared with alum.

3.2.2. Turbidity Removal

Figure 2 shows the evolution of turbidity removal as a function of coagulant dosage. For the pre-hydrolyzed coagulants, three main phases were observed: i) Increasing phase: characterized by a steady increase in turbidity removal, reaching a maximum of 89.3% for PAX-XL6 and 84.6% for PAX-XL6 at 4 mg Al/L; ii) Pseudo-steady-state phase: observed at doses beyond 4 mg Al/L and characterized by relatively stable turbidity removal (89.3-92.6% for PAX-XL6 and 84.6-92.8% for PAX-XL8) as doses increased from 4 to 8 mg Al/L; iii) Decreasing phase: characterized by a gradual decrease in turbidity removal, from 92.6% to 21.0% for PAX-XL6 and from 98.1% to 42.6% for PAX-XL8, as doses increased from 8 mg Al/L to 15 mg Al/L, due to colloids restabilization as described above for color removal [12, 24-26]. The optimal coagulant dose for maximum turbidity removal was 4 mg Al/L.

For Alum, two main phases were observed: i) Increasing phase: characterized by a steady increase in turbidity removal, reaching a maximum of 80.3% at 4 mg/L, and ii) Decreasing phase: observed at doses beyond 4 mg Al/L and characterized by a drop in turbidity removal from 80.3% to 50.3%, due to colloid restabilization and destabilization of the coagulation

process, as reported in previous studies [5]. The optimal coagulant dose for maximum turbidity removal was also 4 mg Al/L.

As shown in Table 3, all coagulants successfully met the WHO turbidity limit (< 5 UTN) at the optimal dose. Based on turbidity removal efficiency, the coagulants ranked as follows: PAX - XL6 > PAX - XL8 > Alum. The results align with the previous studies comparing polyaluminum chloride and aluminum chlorohydrate with alum [5, 27].

A strong correlation was found between turbidity and color (Figure 3). For PAX - XL6 and PAX - XL8, this relationship was linear ($R^2 = 0.97$ and 0.93 respectively). Alum showed a moderate correlation ($R^2 = 0.87$). Since the raw water was collected from a forest lake, the compounds responsible for turbidity were likely suspended solids and hydrophobic colloids (clay, silt, tannins, and organic debris). The same substances contributed to both color and turbidity.

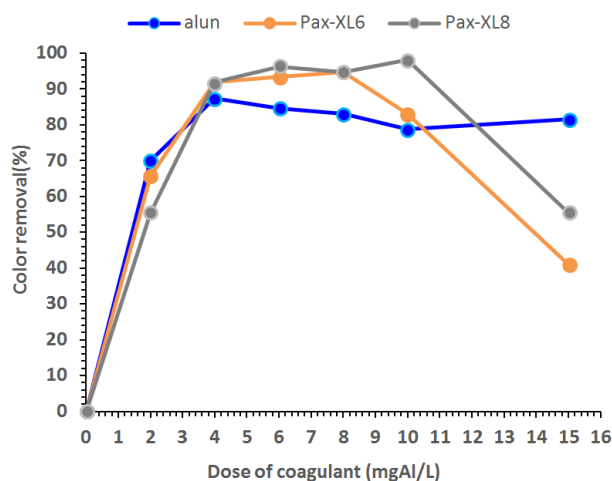


Figure 1. Evolution of color removal as a function of coagulant dosage.

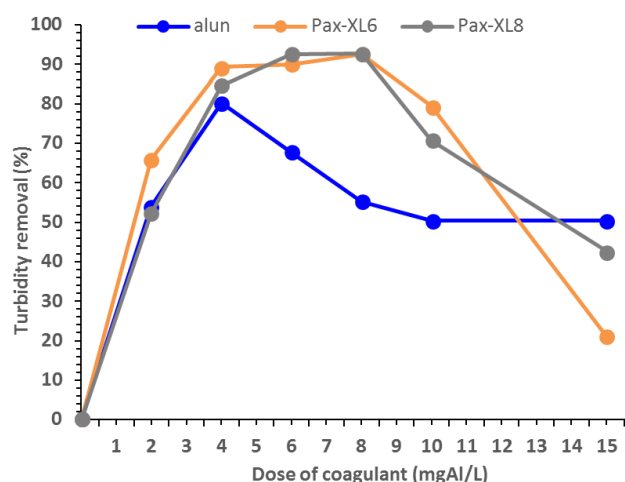


Figure 2. Evolution of turbidity removal as a function of coagulant dosage.

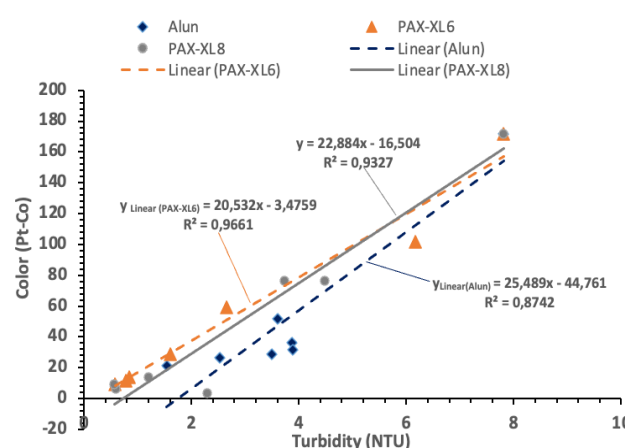


Figure 3. Correlation between color and turbidity.

Table 3. Physicochemical composition of the treated water at optimal coagulant dose (200 rpm followed by 30 rpm, dose: 4 mg Al/l).

Coagulant	Optimal dose (mgAl/l)	Residual color (Pt-Co)	Residual turbidity (NTU)
PAX - XL6	4	14	0,8
PAX - XL8	4	14	1,2
Alum	4	21,5	1,5

3.3. Effects of Coagulant Dose on pH, Alkalinity and Hardness

The pH of water is an important parameter in water chemistry, as it strongly affects the stability of organic colloids, which are more difficult to remove within certain pH ranges

[15, 20, 28]. The change of water pH as a function of coagulant dose is shown in Figure 4. The pre-hydrolyzed coagulants caused only a slight decrease in pH between 0 to 10 mg Al/L. At 15 mg Al/L, pH dropped to 4.81 (PAX-XL6) and 5.40 (PAX-XL8). At the optimal dose (4 mg Al/L), pH remained around 5.57.

In contrast, alum induced pronounced acidification. pH

gradually decreased as doses increased up to 2 mg Al/L, and then dropped steadily, reaching 3.41 at 15 mg Al/L. At the optimum dose (4 mg Al/L), pH was 5.01. Similar trends were reported by Krupińska [20] and Nowacka [5], who observed that alum produced the lowest pH values compared to pre-hydrolyzed coagulants (PAX-XL19H, Flokor 1.2A and PAX-XL10). These coagulants generate polymeric aluminum species, relatively stable and slightly dependent on pH, whereas alum produces monomeric aluminum species that are highly dependent on pH [14, 16, 20, 29].

The evolution of alkalinity as a function of coagulant dose is presented in Figure 5. For both PAX-XL6 and PAX-XL8, alkalinity decreased moderately (from 32 to 29 mg CaCO₃/L) at low doses (< 4 mg Al/L), then decreased further beyond 8 mg Al/L, reaching 6 mg CaCO₃/L (81% reduction) for PAX-XL6 and 13 mg CaCO₃/L (59% reduction) for PAX-XL8 at 15 mg Al/L.

In contrast, alum consumed alkalinity more rapidly: a 47% reduction occurred at 4 mg Al/L, and alkalinity was completely consumed at 8 mg Al/L. These findings are consistent with literature reports indicating higher alkalinity consumption by alum than by pre-hydrolyzed coagulants [5].

Water hardness influences not only human health but also plays a critical role in controlling pipe corrosion. The complex interactions among water quality parameters, and their combined effects on both human health and the stability of distribution infrastructure, highlight the importance of careful and balanced management of these parameters to ensure continuous access to safe, high-quality drinking water.

The effect of coagulant dose on water hardness is shown in Figure 6. Neither the type nor the dose of coagulant significantly affected hardness, which remained close to its initial value. Water hardness, determined by Ca²⁺ and Mg²⁺ concentrations, is a key parameter for water potability and corrosion control. Under the optimal dose, the treated water was therefore classified as “very soft”, consistent with WHO recommendations.

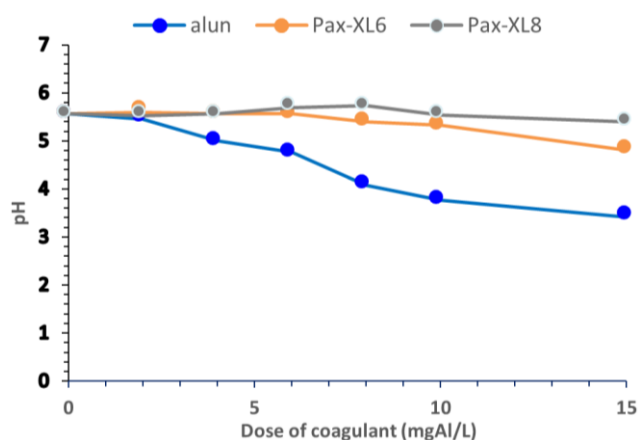


Figure 4. Evolution of pH in treated water as a function of coagulant dosage.

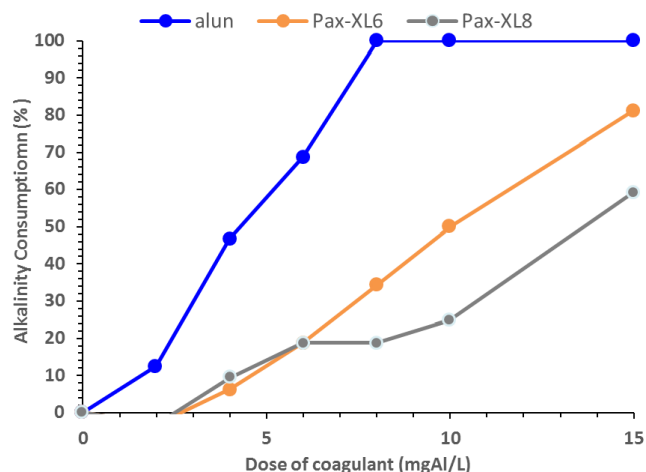


Figure 5. Evolution of alkalinity consumption as a function of coagulant dosage.

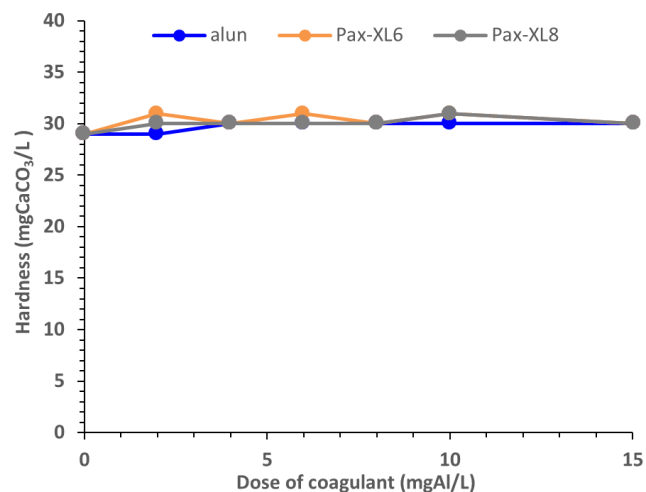


Figure 6. Evolution of water hardness in treated water as a function of coagulant dosage.

4. Conclusion

This study demonstrated that the performance of surface water clarification strongly depends on both the type and dosage of coagulants used. The pre-hydrolyzed coagulants (PAX-XL6 and PAX-XL8) achieved the highest performances in color and turbidity removals, with an optimal dose of 4 mg Al/L. At this dosage, both coagulants met the WHO drinking water standards (color < 15 Pt - Co, turbidity < 5 NTU), whereas alum met only turbidity requirement.

When doses exceeded 4 mg Al/L, the efficiency of all coagulants declined due to colloids restabilization and subsequent destabilization of the coagulation process. None of the tested coagulants significantly affected water hardness. Overall, the pre-hydrolyzed coagulants represent efficient and sustainable alternatives to alum for surface water clarification. To promote large-scale implementation, pilot-scale studies under real operating conditions are recommended to evaluate techno-economic feasibility, operational robustness, and

sanitary compliance.

Abbreviations

PAX-XL6	Polyaluminium Chloride 6
PAX-XL8	Polyaluminium Chloride 8
Alum (ALS)	Aluminium Sulfate
WHO	World Health Organization
CEAEQ	Centre d'Expertise en Analyses Environnementales du Quebec
EDTA	Ethylenediaminetetraacetic Acid

Author Contributions

Brahima Seyhi: Conceptualization, Data curation, Investigation, Methodology, Project administration, Visualization, Writing – original draft

Kassoum Sangare: Data curation, Formal analysis, Methodology, Writing – review & editing

Georges Kouame Kouadio: Formal analysis, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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