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Experimental assessment of coagulation efficiency using aluminum and iron salts

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Abstract. A comprehensive experimental study of the comparative efficiency of traditional and modern coagulants for model wastewater treatment was conducted. The work examined in detail four types of reagents: aluminum sulfate ($Al_2(SO_4)_3$), iron (III) chloride ($FeCl_3$), iron (II) sulfate ($FeSO_4$), and polyaluminum chloride (Aqua-Aurat 30). Critical coagulation process parameters were established: optimal pH values (6.3-8.7 depending on the reagent), dosages (1-2 ml per 50 ml of wastewater), and the necessity of mixing. Special attention was paid to analyzing the influence of these factors on floc formation rate and completeness, as well as the volume and structure of the resulting sediment. Polyaluminum chloride showed the highest efficiency, producing 5 ml of sediment at a minimum dosage of 1 ml/50 ml while significantly improving organoleptic indicators of treated water. These findings enable optimization of coagulant selection for specific wastewater compositions.

1 Introduction

Due to the ever-increasing anthropogenic impact on water bodies, the issue of effective wastewater treatment is becoming particularly relevant. The data obtained in various studies [1-3] confirm that the state of water resources directly affects the ecological state of the environment and human health. Industrial wastewater disposal is a key environmental task today, as the growth of industry affects the pollution of water bodies, which in turn affects not only nature, but also people.

Having analyzed the existing methods of wastewater treatment [4], it can be concluded that each of their methods has its own positive sides and is used for specific requirements in certain conditions. Wastewater treatment with coagulants remains one of the most effective ways of clarifying aquatic environments [5-6]. The effectiveness of coagulation treatment mostly depends on the correct selection of reagents, since different coagulants manifest themselves in different ways and their effectiveness will depend on:

1. characteristics of the treated water (chemical composition);
2. concentrations of pollutants and their nature;
3. physico-chemical conditions of the process (pH, temperature).

Optimal coagulant selection can improve treatment efficiency by 20–40%, reduce reagent consumption, and minimize secondary waste generation.

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Modern water treatment technologies employ various classes of coagulants, with aluminum and iron salts being the most widely used. Traditional inorganic coagulants, such as aluminum sulfate ($Al_2(SO_4)_3$), iron (III) chloride ($FeCl_3$), and ferrous sulfate ($FeSO_4$), remain popular due to their effectiveness in removing suspended solids. Studies [7–8] indicate that beyond standard coagulants, other reagent types—including polyaluminum chloride (aluminum oxychloride, $Aln(OH)_mCl$) — demonstrate notable advantages. Conducting a series of experimental tests will allow for a detailed investigation of the selected coagulants' performance and the identification of the optimal reagent for a given wastewater composition.

2 Conducting experimental research

For conducting experimental studies of purification processes, a model solution was developed to replicate the key characteristics of wastewater. Distilled water was used as the base with initial parameters: $pH = 7.0 \pm 0.2$, electrical conductivity of $2 \pm 1\ \mu S/cm$, zero hardness, and minimal turbidity of $0.5 \pm 0.1\ NTU$. These baseline values were essential for assessing wastewater treatment efficiency.

The following instruments were employed for all measurements: an EcoDigital $pH\ meter$ (pH), a TDS&EC multiparameter tester (electrical conductivity, hardness, temperature), and a ZD-2A digital turbidimeter (turbidity).

The solution was prepared in stages. First, 1.5 g of silicon dioxide (SiO_2) was added to a 1-liter volumetric flask to create turbidity, followed by 0.23 g of chalk ($CaCO_3$) to simulate carbonate hardness. The components were dissolved in 500 mL of distilled water under constant stirring for 30 minutes. Then, a pre-prepared copper sulfate solution (0.5 g $CuSO_4$ in 100 mL water) was introduced gradually with continuous stirring. After achieving homogeneity, the volume was adjusted to 1 liter with distilled water.

Laboratory tests determined the key physicochemical water parameters: turbidity reached $170 \pm 2\ NTU$, $pH = 5.5 \pm 0.1$, specific electrical conductivity was 580±2 µS/cm, and total hardness was 5.8 $°dH$.

Effective coagulation with most reagents requires an alkaline environment. The optimal pH of 8.7 ± 0.3 was achieved by adding 180 ± 5 µL of 1M $NaOH$ solution per 100 mL of treated wastewater. Under these conditions, active formation of flocculent structures was observed, primarily consisting of insoluble copper hydroxides, which subsequently precipitated.

The first reagent studied was aluminum sulfate ($Al_2(SO_4)_3$). This coagulant requires an acidic environment for effective performance, so prior to introduction, the solution pH was adjusted to 6.3 ± 0.2 by adding 100 µL of 1M $NaOH$. The experimental results (Fig. 1-2) showed that increasing the dosage from 1 mL to 2 mL per 50 mL of wastewater did not lead to a significant increase in the volume of sediment formed, which remained stable at 1-1.5 mL on the graduated cylinder scale. It was observed that stirring promoted the formation of more homogeneous sediment without visible fractionation.

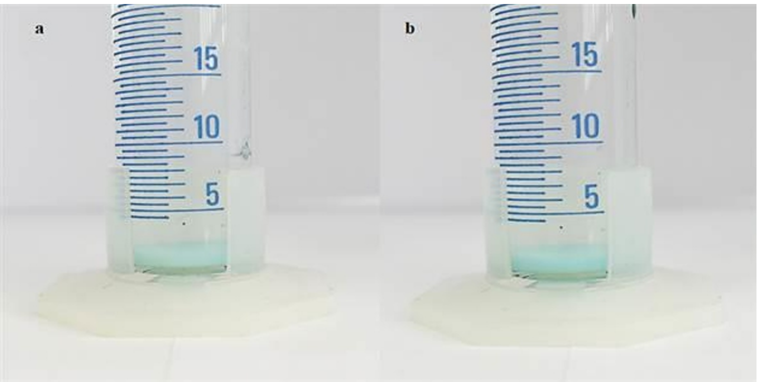

Fig. 1. Test coagulation with $Al_2(SO_4)_3$: (a) - 1 mL with stirring; (b) - 1 mL without stirring

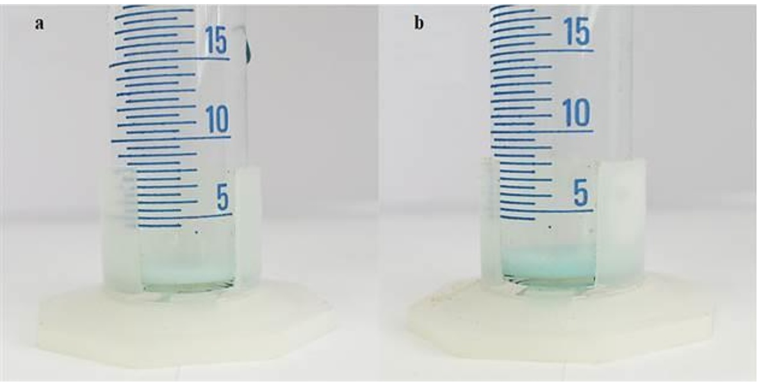

Fig. 2. Test coagulation with $Al_2(SO_4)_3$: (a) - 2 mL with stirring; (b) - 2 mL without stirring

However, the overall purification efficiency turned out to be insufficient for practical application, indicating the limited coagulating capacity of aluminum sulfate under these conditions.

The next stage of the study involved the use of iron (III) chloride ($FeCl_3$). Unlike the previous reagent, this coagulant demonstrated somewhat better results - the sediment volume increased to 1.5-2 ml. However, it was found that increasing the dosage negatively affected the sedimentation process. Visual observation also revealed the presence of residual iron in the solution, which reduced the final transparency of the purified water. It is important to note that during stirring, all components precipitated synchronously without forming additional contaminant flakes. All results of this study are presented in Figures 2 and 3. The experimental data suggest that while iron (III) chloride shows better coagulation performance compared to aluminum sulfate, its practical application may be limited by the negative effects of dosage increases and residual iron content in treated water. Further optimization of process parameters is required to improve the efficiency of iron-based coagulants while maintaining acceptable water quality indicators.

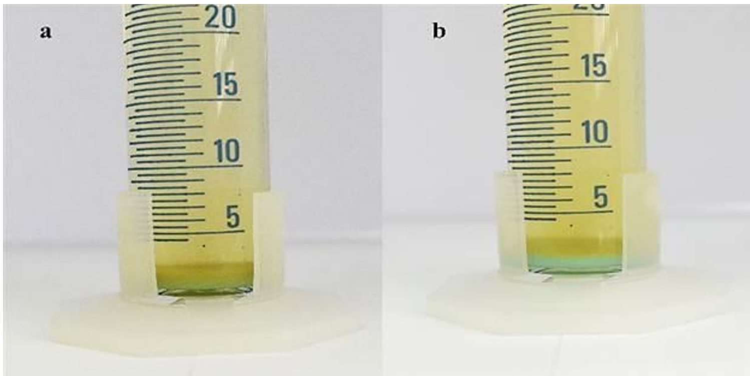

Fig. 3. Test coagulation with $FeCl_3$: (a) - 1 mL with stirring; (b) - 1 mL without stirring

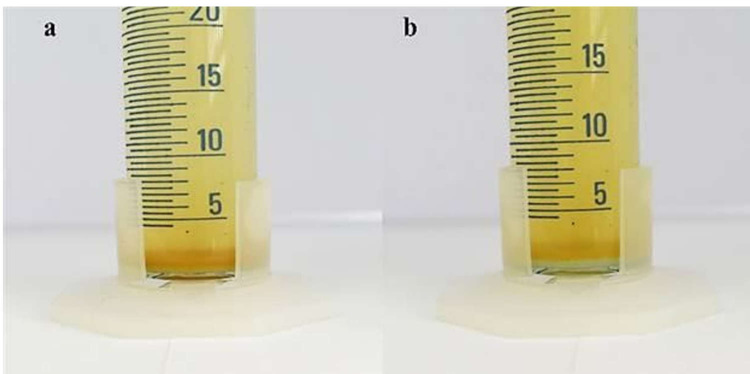

Fig. 4. Test coagulation with $FeCl_3$: (a) - 2 mL with stirring; (b) - 2 mL without stirring

The use of $FeSO_4$ significantly enhanced coagulation performance compared to conventional reagents. The resulting sludge volume reached 2-2.5 mL, representing a 25-30% increase over $FeCl_3$ treatment. Importantly, the mixing process in this case delivered substantially more effective purification of the model solution, as clearly demonstrated in Figures 5-6.

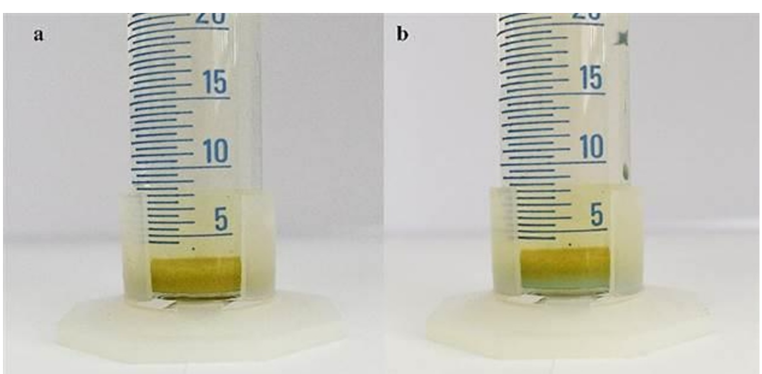

Fig. 5. Test coagulation with $FeSO_4$: (a) - 1 mL with stirring; (b) - 1 mL without stirring

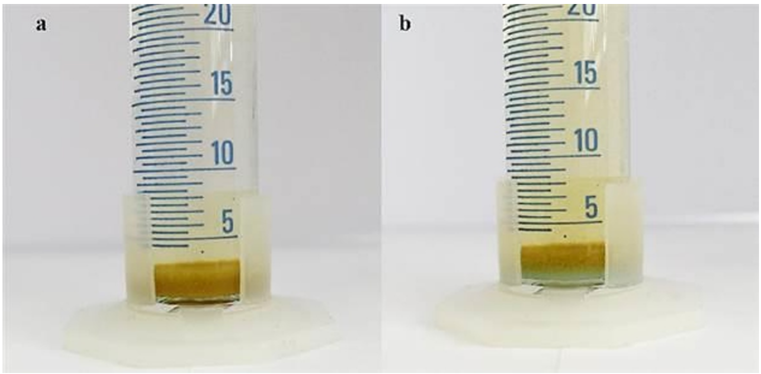

Fig. 6. Test coagulation with $FeSO_4$: (a) - 2 mL with stirring; (b) - 2 mL without stirring

Visual assessment confirmed significant improvement in the water's organoleptic properties after treatment. However, as in previous cases, increasing the dosage from 1 mL to 2 mL did not result in a proportional enhancement of process efficiency.

The best results were obtained using polyaluminum chloride (Aqua-Aurat 30). This coagulant demonstrated exceptional efficiency - the sludge volume reached 5 mL at a dosage of just 1 mL per 50 mL of wastewater, which was 2.5-3 times higher than the performance of other tested reagents. A key observation was that doubling the coagulant dose did not lead to further increase in sludge volume. Notably, the absence of mixing significantly reduced sedimentation efficiency - particles did not settle completely, highlighting the critical importance of this technological parameter (Figs. 7-8). Visually, the treated water showed high clarity, while the resulting sludge had a dense, homogeneous structure.

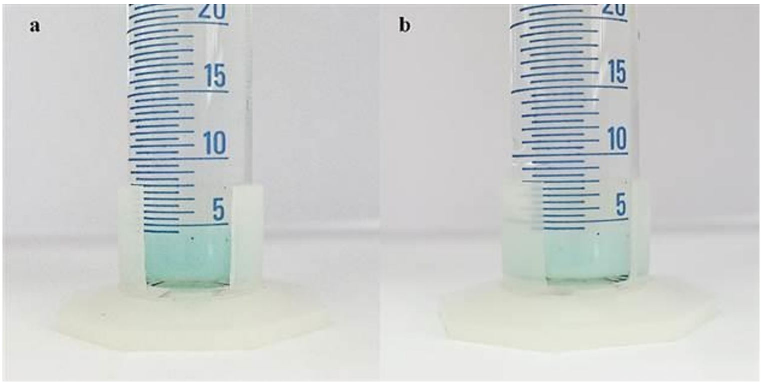

Fig. 7. Test coagulation with Aqua-Aurat 30: (a) - 1 mL with stirring; (b) - 1 mL without stirring

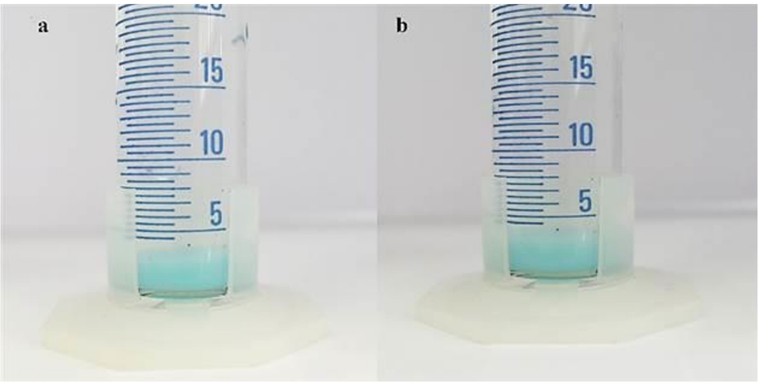

Fig. 8. Test coagulation with Aqua-Aurat 30: (a) - 2 mL with stirring; (b) - 2 mL without stirring

3 Conclusions

Thus, the conducted experimental studies yielded several important conclusions about the comparative effectiveness of various coagulants in wastewater treatment. Polyaluminum chloride (Aqua-Aurat 30) demonstrated the highest efficiency, producing 5 mL of sludge at a minimal dosage of 1 mL per 50 mL of wastewater - 2.5-3 times greater than other tested reagents. Crucially, increasing the coagulant dosage beyond the optimal amount didn't proportionally increase sludge volume, indicating each reagent type has a maximum coagulation capacity.

Significantly, polyaluminum chloride not only achieved the best quantitative results in sludge volume but also delivered superior purification quality in organoleptic parameters - water clarity and absence of residual reagents. The dense, homogeneous sludge structure and complete particle sedimentation (when using proper mixing) further confirmed its technological advantages over traditional iron-based coagulants like $FeSO_4$ and $FeCl_3$. These findings highlight the critical importance of both reagent selection and process parameters (particularly mixing intensity) for optimizing wastewater treatment efficiency.

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