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DEVELOPMENT AND PERFORMANCE ANALYSIS OF BIOPOLYMER-BASED FLOCCULANTS FOR SUSTAINABLE WASTEWATER TREATMENT

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ABSTRACT

Flocculation is a key process in industrial wastewater treatment, traditionally carried out using inorganic coagulants due to their low cost and ease of application. However, their limited flocculation efficiency and residual metal content in treated water restrict their use. Synthetic polymer-based flocculants, while highly efficient at low dosages, present concerns regarding poor biodegradability and the release of residual monomers, which may pose health and environmental risks. In contrast, biopolymer-based flocculants have gained increasing attention for their biodegradability, environmental compatibility, and ability to provide effective pollutant removal. This study reports the development and performance analysis of various biopolymer-based flocculants for the treatment of highly contaminated industrial wastewater. Laboratory, pilot, and industrial-scale experiments were conducted to assess their flocculation efficiency under varying water quality conditions. The results demonstrate that the selected biopolymer flocculants significantly reduce color intensity, suspended solids, and chemical oxygen demand (COD) while minimizing secondary pollution. Furthermore, a techno-economic assessment confirmed their cost-effectiveness compared to conventional chemical treatments. The study provides insights into the flocculation mechanisms of these materials and underscores their potential as sustainable alternatives for large-scale wastewater treatment applications.

Keywords: Biopolymer Flocculants, Wastewater Treatment, Flocculation Efficiency, Biodegradability, Environmental Sustainability, Techno-Economic Analysis

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INTRODUCTION

The growing demand for clean water and the increasing stringency of environmental regulations have intensified the search for sustainable and efficient wastewater treatment technologies. Conventional chemical coagulants and flocculants, though effective, pose challenges such as high cost, secondary pollution, and sludge management issues, thereby driving research toward eco-friendly alternatives.[1] Biopolymer-based flocculants derived from natural sources, including plants, microbes, and agricultural by-products, are emerging as promising substitutes due to their biodegradability, low toxicity, and high efficiency in pollutant removal.[2] These natural polymers, such as chitosan, starch, cellulose derivatives, and microbial extracellular polysaccharides, have demonstrated excellent performance in removing turbidity, heavy metals, dyes, and organic pollutants from diverse wastewater streams.[3,4] Recent studies have expanded the scope of biopolymer flocculants through chemical grafting and functionalization, significantly enhancing their flocculation properties and tolerance to diverse water chemistries.[5] Plant-derived flocculants, such as Tacca leontopetaloides-based biopolymers, have shown remarkable removal efficiencies for turbidity, total suspended solids (TSS), color, and heavy metals, highlighting their potential for industrial-scale applications.[6] Additionally, techno-economic assessments of large-scale production systems indicate that natural biopolymers like Grewia-based coagulants could significantly reduce reliance on synthetic agents while improving overall cost-effectiveness in wastewater management.[7] The monitoring of the physical and chemical indicators of wastewater from silk-reeling production and the specificity of production showed that the composition and contamination of

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wastewater with harmful substances are quite high. The concentrations of pollutants contained in wastewater exceed the MPC values by almost 25-30 times.[8] During the process of flocculation, polymer macromolecules are linked by bridges with colloidal particles. Not the entire macromolecule of the flocculant is adsorbed on the colloid, but part of its segments, the size of which is several orders of magnitude smaller than the size of the colloidal particles.[9,10] Electrostatic forces activate the chemical interaction of macroions of flocculants and the ionized surface of colloids when they have opposite charges.[11] The experimental procedure is similar to determining the doses of mineral coagulants (without lime). The test water is poured into 6-7 glasses (or cylinders) to the mark, and a different amount of the flocculant working solution is introduced into each sample, which corresponds to different doses of the flocculant.[12] Mixing of wastewater and sampling after completion of the treatment process should be carried out in the same way as in previous laboratory work. Recommended doses of flocculants are typically in the range of 5–50 mg/L. However, if overdosed, the cleaning effect is sharply reduced due to the restabilization of colloids, which occurs when particle surfaces become fully saturated with polymer, preventing further bridging.[13] In addition, Uzbek researchers have also conducted notable studies on the application of coagulation and flocculation processes for wastewater treatment. For instance, Amonov et al. investigated the efficiency of aluminum- and iron-based coagulants in treating textile industry effluents, demonstrating significant reductions in turbidity and chemical oxygen demand.[14-16] Shamuratov et al. investigated the utilization of acidic wastewater from the soap industry using high-carbonate phosphorite from Central Kyzylkum, demonstrating its potential for neutralizing acidity and improving the overall treatment efficiency of industrial effluents.[17] Mutalov et al. conducted a study on the flocculation properties of modified polyacrylamide, demonstrating its improved aggregation performance and potential applicability for enhancing sedimentation processes in wastewater treatment systems.[18,19] Amonova et al. studied the use of composite polymeric flocculants for the treatment of food processing wastewater, reporting improved sedimentation rates and enhanced pollutant removal.[20] These studies highlight the growing interest and progress in developing efficient coagulation–flocculation techniques within Uzbekistan for sustainable wastewater management.

This study aims to develop and analyze the performance of novel biopolymer-based flocculants for sustainable wastewater treatment. By integrating physicochemical characterization, flocculation performance evaluation, and environmental impact analysis, this research seeks to advance the application of biopolymer flocculants as viable alternatives to conventional chemical treatments in achieving cleaner water and promoting circular economy practices.

EXPERIMENTAL

Material and Methods

A series of high-molecular-weight polymeric flocculants, including FLP-1, FLK-2, FLG-3, FLU-4, FLPC-5, FLPG-6, FLPU-7, FLKG-8, and FLKU-9, were used in this study. Additionally, polyelectrolytes such as polyacrylamide (PAA), polyethyleneimine (PEI), and sodium carboxymethylcellulose (NaCMC) were applied to enhance flocculation efficiency. Bentonite and kaolin served as adsorbents, while aluminum sulfate and sodium bisulfite were used as mineral coagulants. All chemicals were of analytical grade and used without further purification. Wastewater samples were collected from gas processing and silk-reeling facilities, with initial pollutant concentrations exceeding maximum permissible concentrations (MPCs) by 25–30 times.

General Procedure

The flocculation experiments were carried out using a standard jar-test procedure. Wastewater samples were poured into 6–7 beakers, each containing a different dose of flocculant solution, covering a dosage range between 5 and 50 mg/L. The samples were rapidly mixed for 3–5 minutes, followed by slow mixing for an additional 10–15 minutes to promote floc growth. After mixing, the suspensions were allowed to settle for 20–30 minutes. pH adjustments were made as needed to maintain the optimum range for flocculation, which was determined to be between 7.1 and 8.7. For combined treatment approaches, flocculants were applied in conjunction with coagulants and adsorbents to evaluate synergistic effects on pollutant removal.

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Detection Methods

The efficiency of the treatment was evaluated based on several parameters. Color intensity reduction was measured using a FEK-LF-72M photometric colorimeter with 10 mm cuvettes and appropriate light filters. Chemical oxygen demand (COD) and biological oxygen demand (BOD) were determined using standard titrimetric methods. Concentrations of chloride, sulfate, and ammonium ions were measured via spectrophotometric and titrimetric techniques. The concentrations of petroleum products were determined gravimetrically, and suspended solids were quantified by standard gravimetric analysis.

Analytical Discussion

Experimental results indicated that the effectiveness of flocculation strongly depended on the type and dosage of the applied flocculant. Optimal performance was achieved with the combined use of PAA and NaCMC at a ratio of 1:1.5 and a total dose of 0.25:0.40 mg/L, resulting in a 90–95% reduction in color intensity and a 43–51% decrease in COD. Overdosing of flocculants led to a restabilization of colloidal particles, significantly reducing the treatment efficiency. Moreover, combined treatment using flocculants with coagulants and adsorbents provided the highest purification efficiency, achieving up to 93% color removal and reducing petroleum product concentrations to 6–7 mg/L, while also minimizing overall reagent consumption compared to conventional coagulation methods. These findings confirm that polymeric flocculants, particularly when used in combination with mineral coagulants and sorbents, significantly enhance the treatment efficiency of highly polluted industrial wastewater.

RESULTS AND DISCUSSION

On wastewater of all groups, the high efficiency of using flocculants selected on the basis of the developed methodology and technological parameters of their use was shown. It has been shown that the effectiveness of flocculation treatment technologies, including the stages of mixing, flocculation and clarification, using cationic flocculants of the first and second groups (FLP-1, FLK-2, FLG-3, FLU-4, FLPC-5, FLPG-6, FLPU-7, FLKG-8, FLKU-9) is 93-98%, and has increased by 18-32% compared to schemes without flocculation chambers. For example, the efficiency of wastewater treatment from gas processing plants by sedimentation is 97-98% with an initial concentration of suspended solids of 1300-3500 mg/l and a dose of FLP-1 flocculant of 0.15-0.20 mg/l.[21] This technology was implemented in the design of treatment facilities for gas processing plants in Mubarek and was tested under both pilot and industrial conditions for treating wastewater from a gas processing plant. The developed methodology has shown that it is possible to increase the efficiency of wastewater treatment in existing and widely used treatment schemes that lack flocculation chambers by using high-molecular flocculants from the third group (Table-1). This was confirmed by the results of industrial tests on various types of wastewater. For example, to treat wastewater from a gas processing plant, high purification efficiency was achieved using the FLKU-9 flocculant (Table 1).

Table-1: Efficiency of Using Various Reagents for Treating Wastewater from a Gas Processing Plant

Flocculant	Dose, mg/l	Suspended solids, mg/l		
		before cleaning	after clarifier	//
FLP-1	0,4	1350	180	14
FLC-2	0,4	1410	230	16
FLG-3	0,6	1380	240	19
FLU-4	0,5	1375	195	15
FLPC-5	0,3	1390	140	11
FLPG-6	0,3	1435	165	12
FLPU-7	0,4	1425	160	14
FLCG-8	0,3	1300	130	15
FLCU-9	0,2	1400	105	10

The industrial introduction of high-molecular flocculants instead of inorganic coagulants makes it possible to increase the cleaning efficiency, reduce the consumption of reagents, reduce the amount of sediment formed, and eliminate equipment corrosion. For example, when using the flocculant FLKU-9 in doses of 0.2-0.3 mg/l to treat wastewater FLKU-9 of a gas processing plant, the content of petroleum products is reduced from 23-150 mg/l to 5-7 mg/l, while using aluminum sulfate, up to 1.2-1.5 mg/l. At the same time, reagent consumption is reduced by 50 times, transportation costs are correspondingly reduced, the operation of the reagent facility is facilitated, and working conditions are improved. The annual discharge of pollutants is reduced by 485 tons, including suspended substances by 77 tons, petroleum products by 29 tons, sulfates by 379 tons. A comparison of the technical and economic indicators of existing wastewater treatment schemes using inorganic coagulants and flocculants showed that economic efficiency is achieved only by reducing the cost of reagents if its specific consumption is reduced by at least 25 times, and the cost of the flocculant is no more than the cost of the coagulant than 45 times. For example, a comparative analysis of the costs of reagents - aluminum sulfate and flocculant FLKU-9 for wastewater treatment of a gas processing plant with a flow rate of 600 m 3 / h showed that, despite the high cost, the costs of the flocculant are lower than the costs of aluminum sulfate by 307 thousand soums per year (Table-2).

Table-2: Technical and Economic Indicators of using Flocculant FLKU-9 for Wastewater Treatment of a Gas Processing Plant

Indicators	Mass units	Aluminum sulfate	FLCU-9
Wastewater flow	m^3/h	85	85
Dose of reagent for commercial product	kg/m^3	0,00012	0,002
Reagent consumption	t/day	0,0102	0,016
Reagent consumption	t/year	3,723	1,36
Reagent cost	sum/year	275.000	35.000.000
Reagent costs	mln.sum/year	1,024	47,6
Petroleum products in purified water	mg/l	11-13	6-7

Based on the analysis and systematization of available data on the types and characteristics of flocculants, it is shown that although there is a wide range of brands of flocculants, information about their properties is limited or absent, or large ranges of characteristics are given, making their selection difficult. In the literature and practice of water treatment, there is no clear methodology and recommendations for the selection of alternative reagents and technology for their use, depending on the type of water being treated and its physicochemical characteristics, which limits the mass introduction of flocculants. As a result of a theoretical consideration of the mechanism of flocculation of dispersions and electrokinetic and adsorption studies performed on real wastewater, the electrostatic nature of the adsorption of ionic flocculants with low and high molecular weight on particles of dispersed contaminants was shown, and the optimal parameters for mixing flocculants with wastewater were substantiated.[22] To maximize contaminant recovery, the flocculation process should be carried out within the optimal pH range. It was experimentally determined that the greatest effect of purifying wastewater from silk-reeling enterprises when using FLCU9 as a flocculant is achieved in the range of pH values from 7.1 to 8.7. In this regard, this subsection presents the results of purification of wastewater generated at the stage of boiling, finishing, and dyeing of silk fabric from various impurities (Fig.-1).

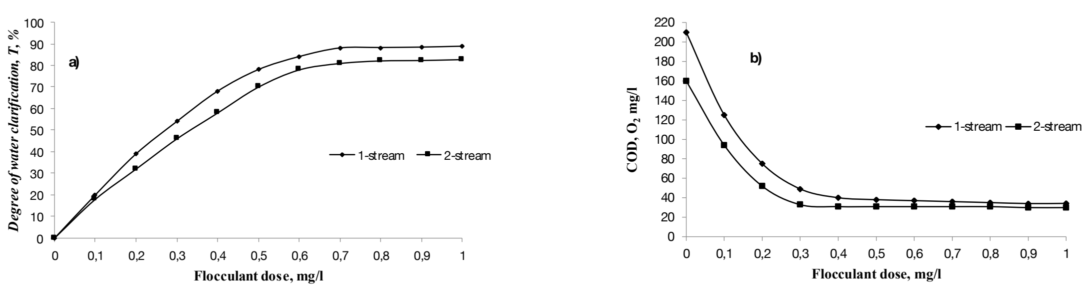

Fig.-1: Dependences of the Degree of Clarification (a), COD (b), on the Flocculant Concentration, obtained in an Experiment on a Model Installation for Wastewater of the second stream with Initial Values of COD = 210 mg/l

The correct choice of reagent largely determines the efficiency of wastewater treatment. In practice, the flotation treatment of industrial wastewater, the selection of the most effective reagents to enhance the

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process of aggregation of released substances is usually carried out experimentally, taking into account the accumulated experience in the treatment of similar types of wastewaters. Analyzing the literature data, we can conclude that the flocculant is the most effective for treating wastewater from silk reeling production, FLCU9.

Thus, for wastewater containing mineral suspended substances, flocculants can be used, which is consistent with the results obtained by other authors when flocculating similar dispersed systems. The effectiveness of using a flocculant for the purification of mineral dispersions is determined by the dominant role of electrostatic interactions. Electrokinetic measurement data was used to determine the optimal dose of the flocculant and its regulation, the degree of filling, 0, of the surface of dispersed particles with flocculant macromolecules, characterizing the actual charge of flocculant macromolecules in solutions, taking into account their conformational state. The problem of modeling the flocculation process as a process of floccule formation and their subsequent sedimentation has been solved. To determine and promptly control the technological parameters of flocculation, it is proposed to use the modified equation of gradient flocculation kinetics as a mathematical model. To optimize technological parameters, the rate constants for flocculation treatment of wastewater from some industries using organic flocculants were determined. The relationship between the viscosity, electrochemical, and flocculating properties of aqueous solutions of ionic flocculants has been established, based on which their priority characteristics have been selected: kinematic or reduced viscosity of the aqueous solution and a charge equal to the limiting value of the electrokinetic potential of quartz particles with flocculant macromolecules adsorbed on them. Based on a study of the effectiveness of different types of flocculants for wastewater treatment, depending on the characteristics and content of dispersed and dissolved contaminants, their priority parameters were determined: the nature and sign of the charge of the dispersed phase, its hydraulic size, the content of dissolved salts, surface-active, and ionic organic substances. It has been scientifically substantiated and experimentally shown that the technology of flocculation wastewater treatment should include the stages of mixing, flocculation, and clarification. It has been established that the conditions of mixing and flocculation depend on the molecular weight of the flocculant. When using flocculants with a molecular weight of more than 3 million, flocculation treatment of wastewater can be carried out according to the scheme: mixing and clarification, with an increase in the mixing time from 0.5-1 to 5-7 minutes.[23,24] Based on a study of the relationship in the flocculant-dispersed phase-dispersion medium system, a methodology for optimizing the flocculation process has been scientifically substantiated and developed, which includes determining factors and their boundary values, classification of flocculants and wastewater, an algorithm for choosing a flocculant, and methods for optimizing technological parameters for treating wastewater from their application. In order to identify the optimal concentration of coagulants and flocculants in the process of wastewater treatment, we studied various concentrations of chemical reagents and determined their optimal doses. According to the graphs of the efficiency of wastewater treatment of dyeing and finishing production, depending on the dose of PAA, its optimal doses were determined, while the COD value of wastewater is reduced by 43-51%, color intensity by 90-95%. Optimal doses of both PAA and mineral coagulants give almost the same cleaning effect in terms of color intensity and COD. Thus, the use of the above reagents can provide a fairly high degree of purification in terms of color intensity, suspended solids, and other important indicators of wastewater pollution.[25,26] Analyzing the existing approaches for removing contaminants from wastewater shows that these methods are highly diverse, yet the need to optimize current practices and develop new, more efficient, and cost-effective technologies for wastewater neutralization remains crucial. In textile production, wastewater is often discharged into sewage systems after dilution to meet maximum permissible concentration (MPC) levels. However, such a practice significantly harms the environment and leads to excessive water consumption. Therefore, enhancing traditional methods and creating innovative approaches for treating wastewater from dyeing and finishing industries is a priority, especially in the context of environmental protection. The treatment of wastewater containing organic dyes and other impurities typically involves adding a specific amount of sorbent to a measured wastewater volume, followed by 3–5 minutes of mixing. Coagulants are then introduced, and the mixture is stirred for an additional 10–15 minutes before allowing the suspension to settle for 20–30 minutes. Discoloration levels were measured using a photometric colorimeter (FEC-LF-72M) with appropriate

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light filters and 10 mm cuvettes, using distilled water as a reference. Data obtained were used to construct graphs illustrating the reduction in color intensity relative to coagulant dosage and adsorbent concentration. These results showed that bentonite alone provides insufficient purification efficiency, making the simultaneous use of coagulants necessary. As expected, combining adsorbents with coagulants and flocculants ensured higher decolorization efficiency and effectively removed fine suspended particles and surfactants. To evaluate the effect of coagulant type on color reduction, experiments varied adsorbent concentrations (1.5–2 mg/L), coagulant dosages (0.4–0.6 mg/L), and flocculant amounts (1.5–2.5 mg/L).

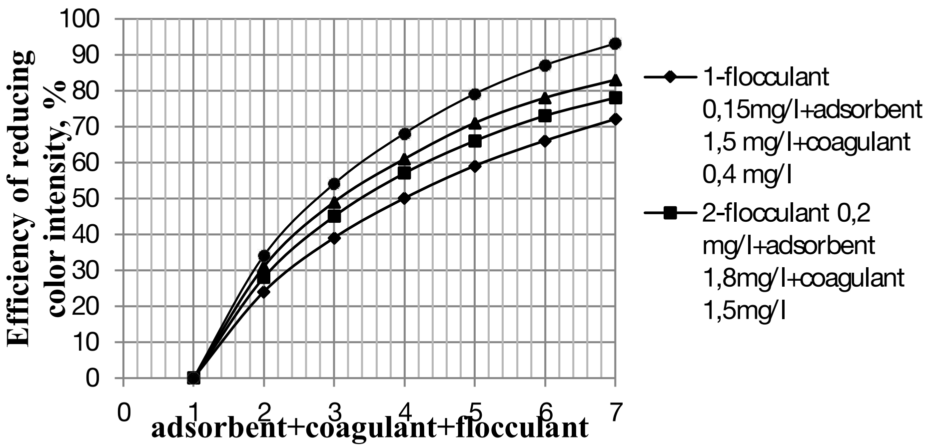

Fig.-2: Change in Color Intensity Depending on the Dose of Flocculants, Coagulants, and Adsorbents at different Ratios

Further research is aimed at studying the clarification of wastewater from dyes, surfactants and other impurities with a coagulant, depending on the ratio of coagulants, and the results obtained are presented in Fig.-2, from which it is clear that the degree of reduction in coloring intensity increases with increasing amount of flocculant, coagulant and sorbent reaches a maximum value of 91-95% at 0.25:0.6:2.5 mg/l. In addition, it was noted that the sorbent exhibits good purification from highly dispersed turbidity and various surfactants present in wastewater. One of the ways to intensify phase separation after the flocculation of metal hydroxides and their saturation with particles or molecules of contaminants is the flocculation of dispersed systems with water-soluble polymers. Reducing the solubility of surfactants and dyes using water-soluble polyelectrolytes also improves the efficiency of wastewater treatment. The phenomenon of flocculation is based on the ability of linear polymer molecules to be adsorbed at different sites, mainly at the ends of chains, on different particles. As a result, a bridging connection is formed between the particles, and relatively loose large aggregates of particles are formed. To purify highly turbid colored waters by settling and clarification in a suspended layer, the use of cationic flocculants (VA-2, VA-212), the consumption of which is 1-10 mg per 1000 mg of solid phase, is effective. The use of flocculant VA-2 also made it possible to increase the filtration speed by 1.5-2 times. The use of polyethylenimine (PEI) flocculant in an amount of 10 kg/dm3 promotes more complete sedimentation of suspended particles, reducing COD and BOD in clarified water. The use of PAA makes it possible to increase the speed of water movement in clarifiers with suspended sediment by 1.2-1.5 times, significantly improves the quality of clarified water, and reduces coagulant consumption by 15-40%. To treat wastewater from textile industry enterprises, the method of reagent pressure flotation is widely used, using flocculants in combination with or without mineral coagulants. Thus, the effect of wastewater treatment for discoloration of the dyeing shop of fine cloth factories when using polyethyleneimine and methylvinylpyrine flocculants at a dose of 8-10 mg/l was 100%, and for the finishing shop, 68-100% at a dose of 40-80 mg/l. The combined use of mineral coagulants - aluminum sulfate and lime with cationic flocculants made it possible to reduce the dose of the mineral coagulant by 50% and significantly increase the effect of wastewater treatment. Surfactants reduce the efficiency of coagulation cleaning and cause the appearance of additional difficult-to-sediment suspension, but according to experimental data from several works, the feasibility of this method is confirmed, since wastewater discoloration occurs by 90-

97% and the COD value decreases by 85-97%.[23-28] Sludge after coagulation treatment has a high humidity of 93.6-99.7% and a rather low ability to dehydrate. The addition of flocculants allows you to obtain a cake with a moisture content of 60-80%. More economical, according to many experts, is the use of filter presses. By adding 10-50% lime or flocculants together with fly ash, cakes containing 45-50% solids are obtained. Researchers have found that flocculants, despite their high cost, have certain advantages over mineral coagulants; they can be used more effectively in significantly lower doses, are non-corrosive, easy to transport, and do not increase the salt content in purified water. Since not only dye ions are negatively charged, but also most colloidal and mineral contaminants in wastewater, the use of cationic flocculants can be more effective than others. Experts believe that when considering the phenomena occurring in the "water-impurities" system, in the case of adding flocculants, the physical and chemical properties of the impurities and their dispersed composition are important. Physico-chemical transformations in the system under consideration are primarily due to the forces of chemical interaction, which are stimulated by electrostatic forces and forces of internal interaction (Vander Waals). During the process of flocculation, polymer macromolecules are linked by bridges with colloidal particles. Not the entire macromolecule of the flocculant is adsorbed on the colloid, but part of its segments, the size of which is several orders of magnitude smaller than the size of the colloidal particles. Electrostatic forces activate the chemical interaction of macroions of flocculants and the ionized surface of colloids when they have opposite charges. If the flocculant is overdosed, the cleaning effect is sharply reduced, since this has a stabilization effect. It has been established that the use of PAA as a polyelectrolyte, despite its high cost, has certain advantages over mineral coagulants - they are effective and can be used in significantly lower doses, are non-corrosive, are easily transported, reduce the dose of mineral coagulants and, accordingly, the volume of precipitation and do not increase the salt content of the treated water. Therefore, the use of flocculants leads to an increased effect of removing various impurities from wastewater. As we know, the flocculating abilities of polymers in wastewater treatment are more effective when used together. In this regard, this article presents the results of wastewater treatment with the combined use of polyacrylamide (PAA) polymers and their sodium salt, as well as carboxymethylcellulose (NaCMS) at various doses and in the presence of coagulants, aluminum sulfate and sodium bisulfite. The results of experiments to study the efficiency of wastewater treatment depending on the dose of flocculants PAA and NaCMC are presented in Table-3. The studies were carried out using samples of PAA with a molecular weight of 10 and NaCMC with a molecular weight of 7 thousand. The most effective effect is exerted by PAA and NaCMC at a ratio of 1:1.5, respectively, in terms of the values of COD and various ions included in the wastewater; their use in doses of 0.25:0.40 mg/l is more effective than PAA: NaCMC = 0.20:0.30 mg/l. Therefore, further experiments were carried out with the combined use of PAA: NaCMC = 0.25: 0.40 mg/l.

To maximize the extraction of contaminants, the flocculation process should be carried out in the range of optimal pH values. It was experimentally determined that the greatest effect of wastewater treatment from textile enterprises when using PAA as a flocculant is achieved in the range of pH values from 7.5 to 9.

Table-3: Reducing the Concentration of Chlorides, Sulfates, and Ammonium Ions during Wastewater Treatment of the Mubarek Gas Processing Plant

Water characteristics	Flocculant ratio PAA and NaCMC		Ion concentrations, mg/l				Cleaning efficiency, %
	Ratio	Total dose, mg/l	Chlorides	Sulfides	Ammonium	pH	
Before cleaning	-	-	88,6	50	2,2	8,3	-
Sorption on bentonite	1,0:0,5	0,25	43,2	51,0	0,6	6,6	64,4
	1,0:1,0	0,40	65,4	68,4	1,0	6,8	81,2
	1,0:1,5	0,55	83,6	79,6	1,4	7,1	84,40

	1,0:2,0	0,70	84,0	91,2	1,80	7,2	93,6
Sorption on kaolin	1,0:0,5	0,25	40,20	42,6	0,45	7,1	62,82
	1,0:1,0	0,40	56,20	61,4	0,9	7,3	80,30
	1,0:1,5	0,55	64,30	82,0	1,2	7,4	82,20
	1,0:2,0	0,70	71,0	87,3	1,6	7,5	91,10

CONCLUSION

The findings of this study emphasize that the selection of highly efficient flocculants is critical for achieving effective removal of diverse contaminants from industrial wastewater. Environmentally friendly flocculants produced through simple and economically viable processes demonstrate not only high removal efficiencies but also the formation of denser and more stable flocs, making them promising candidates for practical large-scale applications. The results indicate that optimal doses of polyacrylamide reduce the color intensity of wastewater by approximately 82–95 %, depending on the initial water composition, while simultaneously decreasing the required amounts of mineral coagulants and, consequently, the volume of sludge generated. Given that most water-soluble dyes in textile effluents are anionic, the application of cationic flocculants substantially enhances dye removal efficiency, providing a sustainable and cost-effective approach to wastewater treatment.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is directly aligned with SDG-6: *Clean Water and Sanitation.* All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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