

Evaluation of the efficiency of a biocoagulant-based technological scheme for municipal wastewater treatment

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ABSTRACT

This study investigated the potential application of a microorganism-derived biocoagulant based on the bacterial strain *Acidithiobacillus ferrooxidans Ach1* to improve the treatment efficiency of wastewater containing organic pollutants. The relevance of the study is associated with the high level of organic and petroleum contamination of wastewater in Kazakhstan, including Shymkent, and the need to improve conventional wastewater treatment technologies. Municipal wastewater from Shymkent was used as the research object. The *A. ferrooxidans Ach1* strain was isolated from polymetallic slags and cultivated in Silverman–Lundgren 9K nutrient medium. During microbial cultivation, Fe^{2+} ions were oxidized to Fe^{3+} , resulting in the biological formation of ferric sulfate, which served as the basis for the microorganism-derived biocoagulant. The main physicochemical characteristics of the wastewater, including chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), phosphates, petroleum products, and oils, were determined. The results showed that the concentrations of COD, phosphates, petroleum products, and oils in the municipal wastewater exceeded the permissible levels. Based on the experimental findings, a technological scheme integrating mechanical, biocoagulation, and biological treatment stages was proposed. The developed technology has the potential to partially or completely replace conventional chemical coagulants, reduce chemical reagent consumption, and improve the environmental sustainability of wastewater treatment. The findings demonstrate the scientific and practical potential of *A. ferrooxidans Ach1*-derived biocoagulation for the treatment of organic wastewater.

Keywords: wastewater, biological treatment, thionic bacteria, environment, biocoagulation.

INTRODUCTION

In recent years, wastewater treatment has become one of the most pressing environmental challenges worldwide, including in the Republic of Kazakhstan. Discharge of untreated wastewater has a significant adverse impact on the environment; therefore, effective wastewater treatment has become an essential prerequisite for sustainable development and environmental protection (Alturki et al., 2023).

Globally, approximately 410 billion m³ of wastewater is generated annually. Due to the deterioration of treatment infrastructure and the absence of efficient treatment systems, a considerable proportion of industrial wastewater is

discharged into the environment without adequate purification (Al-Ani et. al., 2019).

Kazakhstan is classified among the countries experiencing significant water resource scarcity. At present, nearly 50% of the country's wastewater is discharged into surface water bodies without sufficient treatment. This situation is mainly attributed to the application of outdated wastewater treatment technologies in industrial and energy sectors. In many regions, wastewater treatment facilities have been operating for decades without substantial modernization. Consequently, these conditions pose serious threats to aquatic ecosystems, environmental quality, and public health. Over the past decade, the annual volume of industrial wastewater generated in Kazakhstan has increased from

3,594.11 million m³ to 6,039.00 million m³, whereas the volume of treated wastewater has risen only from 525.1 million m³ to 662.2 million m³, indicating that only about 11% of wastewater undergoes treatment (Akmaral et al., 2023).

A wide range of wastewater treatment technologies is currently available for the removal of organic contaminants. These include mechanical methods such as screening, sedimentation, centrifugation, and filtration; physicochemical methods including adsorption, aeration, extraction, coagulation (Hassan et al., 2023), flotation (Falconi et al., 2023), electrolysis (Tabelini et al., 2023), ion exchange, and crystallization; and biological treatment processes employing biofilters (Taşdemir et al., 2021), oxidation tanks, activated sludge systems (aeration tanks), submerged biofilters, and anaerobic biofilters. Among these technologies, biological treatment is widely recognized as one of the most environmentally friendly and effective approaches. Biological processes typically utilize activated sludge or microbial consortia capable of removing up to 85% of organic pollutants from wastewater (Jachimowicz et al., 2022).

Coagulation is the process by which dispersed particles aggregate to form larger flocs through physicochemical interactions. In wastewater treatment, coagulation is primarily applied to accelerate the removal of fine suspended particles and emulsified substances. This process may occur naturally or be induced by physical or chemical factors; however, in industrial practice it is generally achieved through the addition of coagulants (Kurniawan et al., 2025). Coagulants form hydrated metal oxide flocs that readily settle under gravity, entrapping colloidal and suspended particles. Since colloidal particles usually possess a weak negative surface charge whereas the flocs carry a positive charge, electrostatic attraction promotes aggregation. Conventional coagulants include aluminum sulfate (Al₂(SO₄)₃), ferric chloride (FeCl₃), ferric sulfate (Fe₂(SO₄)₃), or their mixtures. The selection of an appropriate coagulant depends on its chemical composition, physicochemical properties, treatment efficiency, and economic feasibility (Issayeva et al., 2022).

Recent studies have introduced biological components into the coagulation process, leading to the development of biocoagulation technologies. For example, Shevkoplyas and Doroshkevich (2021) demonstrated that exoproteins produced by micromycetes interact with potassium humates to form high-molecular-weight

complexes that subsequently condense and precipitate as coagulates. Potassium humates used in their study were obtained from the water-soluble fraction of brown coal from the Dnieper coal basin using conventional extraction techniques (Chen et al., 2025).

Biological treatment based on heterotrophic microorganisms is considered one of the most promising directions in wastewater biotechnology. Hydrocarbon degradation by these microorganisms is associated with their ability to assimilate hydrocarbons as a carbon source. Since petroleum hydrocarbons contain highly reduced chemical bonds, their microbial degradation requires aerobic oxidation (Di Berardino, 2019). Commonly applied heterotrophic bacteria include *Paracoccus denitrificans* (Ge et al., 2018), *Pseudomonas putida* (Ma et al., 2023), *Pseudomonas alcaligenes* (Ma et al., 2025), and *Pseudomonas veronii*, all of which metabolize a broad spectrum of organic compounds during their growth.

In Kazakhstan, phototrophic microalgae such as *Chlorella vulgaris* KAI and *Oocystis borgei* ATP have been successfully applied for the treatment of phosphorus-containing wastewater (Syzykova et al., 2022). In addition, phototrophic microorganisms including *Scenedesmus quadricauda* and *Synechocystis* sp. have demonstrated potential for the biotechnological remediation of water bodies contaminated with radioactive waste (Rahimi et al., 2025).

However, the existing approaches mainly focus on the use of heterotrophic microorganisms or conventional chemical coagulants, while the potential of chemolithotrophic microorganisms as a source of biologically generated coagulants remains insufficiently explored. The scientific novelty of the present study lies in the development and evaluation of a microorganism-derived biocoagulant based on *A. ferrooxidans* AchI, in which the biological oxidation of Fe²⁺ to Fe³⁺ is utilized for the in situ generation of ferric sulfate as the active coagulating component. In contrast to conventional chemical coagulation, this approach integrates microbial cultivation and coagulant production into a single biotechnological process, providing a basis for reducing the direct consumption of externally supplied chemical coagulants. The study further proposes the integration of the produced biocoagulant into a combined mechanical–biocoagulation–biological treatment scheme for municipal wastewater, thereby linking microbial synthesis of the coagulant with

its practical application in wastewater treatment (Kurade et al., 2016). Therefore, the aim of the present study was to evaluate the efficiency of an industrial wastewater treatment technology based on the application of a microorganism-derived biocoagulant and to assess its applicability under industrial operating conditions.

MATERIALS AND METHODS OF RESEARCH

The strain *A. ferrooxidans Ach1*, isolated from polymetallic slags in the Ashysai settlement, was used in this study. These thiobacteria (Figure 1) are typically single, occasionally paired, short rod-shaped cells measuring $0.4 \times (0.8\text{--}1.0) \mu\text{m}$. They are gram-negative, non-spore-forming possess a single polar flagellum, and are capable of oxidizing ferrous iron to ferric iron in acidic media. They reproduce by binary fission.

Isolation and cultivation of thiobacteria were carried out by the limit dilution method in accordance with GOST 26670-91. The strains of thiobacteria *A. ferrooxidans Ach1* were grown on Silverman–Lundgren 9K nutrient medium with the following composition (g/L): $(\text{NH}_4)_2\text{SO}_4$ – 2.0; K_2HPO_4 – 1.0; MgSO_4 – 0.5; NaCl – 0.2; $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ – 44.2; H_2O – 1 L; the pH was adjusted to 1.0 with H_2SO_4 . The suspension of the strains was inoculated into the nutrient medium at a medium-to-suspension ratio of 5:1. Cultivation was performed at 25–32 °C with continuous aeration. The bacteria required for the study were inoculated onto selective nutrient medium using a TC-1/80

SPU TU 9452-002-00141798-97 model thermostat. In studies on the use of *A. ferrooxidans* bacteria for purifying a model solution, the Fe^{2+} and Fe^{3+} content was determined using a complexometric method. «Tauda» and «Mikmed-5» microscopes were used for microscopic studies.

Municipal domestic wastewater collected from “Su Resurstary-Marketing” LLP (Shymkent, Kazakhstan) was used as the study object. Wastewater samples were collected in tightly sealed glass and plastic containers and stored at a temperature of ≤ 4.0 °C until analysis.

Sampling procedures and hydrochemical analyses were performed in accordance with the following national standards: GOST 59024-2020 “Water. General requirements for sampling”; GOST 26449.1-85 “Wastewater. Gravimetric determination of dry residue”; Guideline RD 52.24.382-2006 “Photometric determination of phosphate mass concentration in water”; ST RK ISO 9297-2008 “Water quality. Determination of chloride content by the Mohr method”; GOST 3351-74 “Drinking water. Methods for determining taste, odor, and transparency”; GOST 26449.1-85 “Water. Titrimetric determination of ammonium nitrogen”; GOST 4979-49 “Domestic drinking and industrial water supply. Methods of chemical analysis”; GOST 4151-72 “Drinking water. Methods for determination of total hardness”; and PND F 14.1:2.122-97 “Drinking water. Quantitative chemical analysis. Method for measuring the mass concentration of oils and fats in surface and wastewater”.

For odor determination, water samples were transferred into airtight flasks to prevent contact

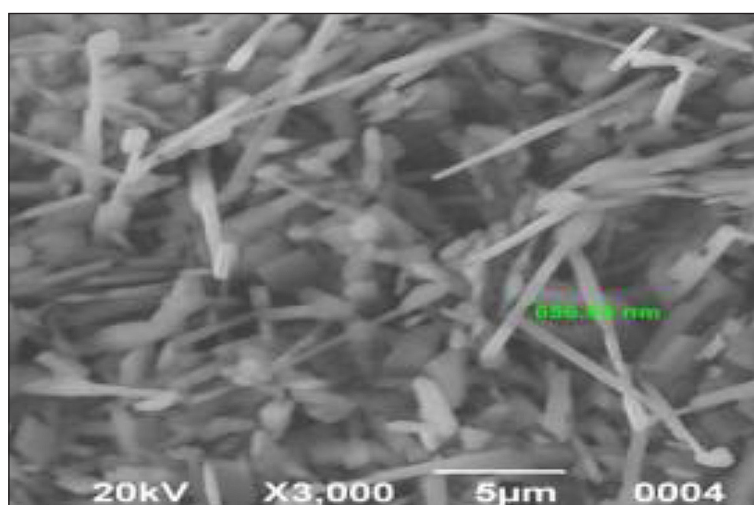


Figure 1. Microscopic image of the bacterial strain *Acidithiobacillus ferrooxidans Ach1*

with atmospheric oxygen. The sealed samples were allowed to stand for several hours before organoleptic evaluation. Water temperature was measured by immersing a thermometer directly into the sample and allowing it to equilibrate for 5 min.

The chemical oxygen demand (COD) was determined according to GOST 31859-2012 “Water. Determination of chemical oxygen demand”. Biochemical oxygen demand (BOD₅) was measured following RD 52.24.420-2006 “Methods for determination of biochemical oxygen demand in wastewater”. The pH of the wastewater samples was measured using a WTW Multi 340i multiparameter meter.

Following mechanical pretreatment, the biocoagulant was added to the wastewater at a dosage of 5.5 ± 0.5 g/L. The wastewater was then mixed for 15 min to ensure uniform distribution of the biocoagulant and effective interaction with the pollutants. After mixing, the treated wastewater was allowed to settle for 1 h. The biocoagulant was prepared using an iron-oxidizing bacterial culture, with periodic supplementation of FeSO₄·7H₂O at 5.5 ± 0.5 g/L during cultivation to maintain bacterial iron-oxidizing activity and continuous ferric iron production. The bacterial population reached approximately 10^7 – 10^8 cells/mL. The oxidation of ferrous iron (Fe²⁺) to ferric iron (Fe³⁺) was visually confirmed by the gradual color change of the culture medium from transparent to reddish-brown.

All experiments were performed in triplicate, and the results are presented as mean $\pm$ standard deviation (SD). Statistical calculations were performed using Microsoft Excel. Arithmetic mean values and standard deviations were calculated according to the method described by Volkov P.A

RESULTS AND DISCUSSION

Characteristics of the *A. ferrooxidans Ach1* strain

Microscopic examination confirmed that the obtained strain belongs to the group of thiobacteria. Cells of the genus *Acidithiobacillus* are Gram-negative, rod-shaped, measuring 0.3 – 0.4×0.7 – 1.7 μ m, and motile by means of polar flagella. They are non-spore-forming and aerobic. The optimal growth temperature ranges from +30 to +35 °C. Cell division occurs by transverse binary fission. During oxidation processes, ferrous iron

(Fe²⁺) is converted to ferric iron (Fe³⁺). The strain is capable of oxidizing elemental sulfur, its compounds, and heavy metal sulfides. Cultivation was carried out in 9K nutrient medium for 4 days.

Laboratory studies demonstrated that ferric iron- or aluminum-based coagulants commonly used for industrial wastewater treatment can be replaced by a biocoagulant derived from the *A. ferrooxidans Ach1* bacterial suspension containing biologically produced Fe₂(SO₄)₃. These microorganisms occupy a unique position among thiobacteria because, in addition to growing autotrophically through the oxidation of sulfur compounds, they are able to derive energy from the oxidation of ferrous iron. During this process, the oxidized iron does not accumulate as structural deposits within the bacterial cells (Struk-Sokołowska et al., 2024). Therefore, in the present study, a microorganism-derived biocoagulant produced using the *A. ferrooxidans Ach1* bacterial strain was applied for wastewater treatment.

Characteristics of municipal wastewater

The physicochemical characteristics of municipal wastewater collected from the primary influent of the wastewater treatment facility in Shymkent were determined before the application of the microorganism-derived biocoagulant. The initial wastewater characteristics are presented in Table 1. The wastewater was characterized by elevated concentrations of COD, ammonium nitrogen, phosphates, petroleum products, and oils and fats. According to the data presented in Table 1, the biochemical oxygen demand (BOD₅) of the municipal wastewater was 2.9 times lower than the maximum permissible concentration (MPC). This indicates the presence of compounds that are resistant or only slowly susceptible to biochemical oxidation.

Chemical oxygen demand (COD) is a widely used indicator for assessing the degree of pollution in wastewater and natural water bodies. The analytical results showed that the COD of the municipal wastewater was 11.9 times higher than the maximum permissible concentration, indicating a high level of organic pollution.

Phosphates are essential nutrients that regulate the growth of aquatic plants and fish populations (Wang et al., 2011). As shown in Table 1, the phosphate concentration in the wastewater exceeded the maximum permissible concentration by a factor of 10.3. Elevated phosphate levels may promote eutrophication, leading to excessive

Table 1. Chemical composition of municipal wastewater

№	Parameters	Permissible concentrations of pollutants	Characteristics of wastewater entering the treatment facility
1	Dry residue, mg/L	n/d	816.0
2	COD, mg/L	27.3 ± 0.1	326.7 ± 0.1
3	BOD ₅ , mg/L	425.0 ± 0.1	147.1 ± 0.1
4	Chlorides, mg/L	184.0 ± 0.1	87.9 ± 0.1
5	Sulfates, mg/L	350.0 ± 0.1	173.8 ± 0.1
5	Ammonium nitrogen, mg/L	10.7 ± 0.5	28.3 ± 0.1
6	Nitrites, mg/L	1.2 ± 0.1	0.2 ± 0.1
7	Nitrates, mg/L	13.4 ± 0.1	0.4 ± 0.1
8	Phosphates, mg/L	0.5 ± 0.1	4.9 ± 0.1
9	Petroleum products, mg/L	0.1 ± 0.1	2.05 ± 0.1
10	Oils and fats, mg/L	1.7 ± 0.1	3.5 ± 0.1
11	Phenol, mg/L	n/d	0.1 ± 0.1
12	Temperature, °C	30 °C not exceed	18.5
13	Transparency, cm	n/d	1.1
14	pH	6.0–9.0	8.2

Note: n/d – not determined.

algal growth, depletion of dissolved oxygen, and deterioration of aquatic ecosystems.

The concentrations of oils and petroleum products exceeded the maximum permissible concentrations by approximately 20-fold. These pollutants inhibit the photosynthetic activity of aquatic plants by forming a surface film that reduces light penetration into the water column, thereby decreasing phytoplankton productivity and disrupting the aquatic food chain. In contrast, the concentrations of sulfates and chlorides remained within the permissible regulatory limits.

The physical characteristics of wastewater also provide important information regarding the degree of contamination and the efficiency of treatment processes. Organoleptic analysis revealed that the wastewater was colorless but possessed a strong odor. The measured temperature was within the normal operating range for biological treatment processes. Water temperature is an important ecological parameter because it directly influences physicochemical reactions and the metabolic activity of aquatic microorganisms.

Efficiency of the *A. ferrooxidans Ach1*-derived biocoagulant

The treatment experiments demonstrated the potential of the *A. ferrooxidans Ach1*-derived biocoagulant for reducing the concentration of several pollutants in municipal wastewater. The

principle of the proposed approach is based on the biological oxidation of Fe^{2+} to Fe^{3+} by *A. ferrooxidans Ach1* and the formation of ferric sulfate, which acts as the active coagulating component. During cultivation, the microorganism oxidizes ferrous iron under aerobic conditions, providing the basis for the biological production of the ferric sulfate-containing biocoagulant.

A particularly pronounced effect was observed for COD. The initial COD concentration of the municipal wastewater was 326.7 ± 0.1 mg/L. Following treatment with the *A. ferrooxidans Ach1*-derived biocoagulant, COD decreased to 76.1 ± 1.4 mg/L. For comparison, treatment using conventional FeCl_3 resulted in a COD concentration of 107.0 ± 2.6 mg/L. Thus, based on the initial and final concentrations, the calculated COD removal was approximately 76.7% for the biocoagulant treatment and 67.2% for FeCl_3 . These results indicate a higher COD reduction under the tested conditions when the microorganism-derived ferric sulfate was used instead of conventional ferric chloride.

The biocoagulant also demonstrated a positive effect on BOD₅. The initial BOD₅ concentration was 147.1 ± 0.1 mg/L and decreased to 70.0 ± 0.1 mg/L after biocoagulation. The corresponding calculated removal efficiency was approximately 52.4%. In comparison, the use of FeCl_3 reduced BOD₅ to 101.0 ± 0.1 mg/L. The greater reduction observed with the

microorganism-derived biocoagulant indicates that the proposed treatment can contribute to the removal of biodegradable and particulate organic matter from municipal wastewater.

The concentration of ammonium nitrogen decreased from 28.3 ± 0.1 mg/L in the untreated wastewater to 12.0 ± 0.1 mg/L after biocoagulation. The reported removal efficiency was $57.5 \pm 3.2\%$. This result demonstrates that the biocoagulation stage can contribute to the reduction of nitrogen-containing pollutants, although additional biological treatment would be required for more complete nitrogen removal.

A considerable reduction was also observed for phosphate compounds. The initial phosphate concentration of 4.9 ± 0.1 mg/L decreased to 1.3 ± 0.1 mg/L after treatment, corresponding to a reported removal efficiency of $73.7 \pm 6.5\%$. The observed phosphate reduction is particularly important because excessive phosphorus discharge may promote eutrophication in receiving water bodies.

The highest treatment efficiency was observed for petroleum products. Their concentration decreased from 2.05 ± 0.1 mg/L before treatment to 0.1 ± 0.1 mg/L after biocoagulation. The corresponding removal efficiency reached $95.1 \pm 4.5\%$. This result demonstrates the considerable potential of the *A. ferrooxidans Ach1*-derived biocoagulant for removing hydrophobic and emulsified petroleum-related contaminants from wastewater. The treatment also demonstrated a substantial effect on phenolic compounds. Based on the fluorimetric determination of phenol before and after treatment, a removal efficiency of $75.0 \pm 6.8\%$ was achieved. The obtained result indicates that the biocoagulation process can contribute to the removal of phenolic pollutants; however, the mechanism of phenol removal should be considered in combination with adsorption and precipitation processes associated with the ferric hydroxide-containing flocs. In contrast, the removal of chlorides was limited. The efficiency of chloride removal during biocoagulation was only 5.1%. Therefore, the proposed biocoagulation stage should not be considered an effective treatment method for dissolved chloride ions. Similarly, the removal of nitrate and nitrite compounds was insufficient for considering biocoagulation as a stand-alone treatment for these pollutants. These results demonstrate that the proposed process is selective with respect to pollutant type and should be integrated with subsequent biological treatment stages.

The observed treatment effects can be associated with the formation of biologically generated ferric sulfate during the cultivation of *A. ferrooxidans Ach1*. The oxidation of Fe^{2+} to Fe^{3+} provides the active iron component required for coagulation. Ferric iron can subsequently participate in hydrolysis and floc formation, facilitating the aggregation and removal of suspended, colloidal, and partially emulsified pollutants. The results obtained in the present study are consistent with the potential of *A. ferrooxidans*-derived biogenic flocculants reported in previous research, where microorganism-derived flocculating components were investigated for wastewater and sludge treatment.

Overall, the experimental results demonstrate that the microorganism-derived biocoagulant was particularly effective in reducing petroleum products, COD, phosphates, phenols, and ammonium nitrogen. At the same time, its low efficiency toward chlorides indicates that biocoagulation should be considered as one stage of an integrated wastewater treatment process rather than as a universal replacement for all treatment technologies.

Integration of biocoagulation into the wastewater treatment scheme

Based on the experimental results, a technological scheme integrating mechanical, biocoagulation, filtration, and biological treatment stages was developed for municipal wastewater treatment in Shymkent. The proposed treatment sequence is presented in Figure 2.

1. The treatment process begins with the influent receiving chamber, where incoming wastewater is collected before treatment.
2. The wastewater is then subjected to preliminary mechanical treatment. This stage typically includes screens or comminutors, grit chambers, and sedimentation tanks to remove coarse suspended solids and reduce the organic load without significant energy consumption, thereby improving the operational stability of downstream biological treatment units. In the proposed process, a grit chamber is employed to remove large mineral particles and prevent their accumulation in sedimentation tanks and sludge digesters.
3. After mechanical treatment, the wastewater flows through a Venturi flume, which is used to measure the flow rate and hydraulic velocity of the incoming wastewater.
4. The wastewater is subsequently collected in a

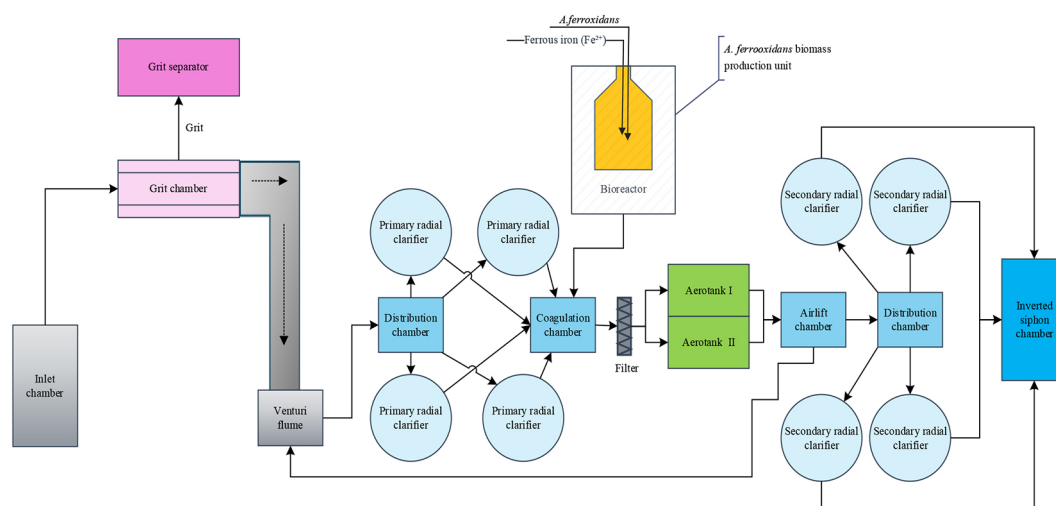


Figure 2. Technological flow diagram for municipal wastewater treatment using a biocoagulant in Shymkent

distribution chamber and directed to the primary radial clarifiers. Primary sedimentation is widely used to remove suspended and settleable solids and represents one of the principal units of mechanical wastewater treatment. In biological treatment plants, primary clarifiers are installed upstream of the biological treatment units when the concentration of suspended solids in the influent exceeds 150 mg/L. Secondary clarifiers are subsequently used to separate activated sludge or biofilm biomass from the treated effluent before discharge or further treatment.

5. In the next stage of the treatment process, the effluent from the primary radial clarifier is collected in a distribution chamber. At this point, a microorganism-derived biocoagulant produced in a dedicated bioreactor is introduced into the wastewater. The bioreactor is used for the cultivation of *Acidithiobacillus ferrooxidans Ach1* in Silverman–Lundgren 9K nutrient medium. To ensure efficient oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), the culture is continuously aerated and maintained at an operating temperature of 25–30 °C. In addition, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ is continuously supplied to the bioreactor at a concentration of $5.5 \pm 0.1 \text{ g L}^{-1} \text{ day}^{-1}$ as the ferrous iron source for biological oxidation and ferric sulfate production. Following biocoagulation, the treated wastewater passes through a filtration unit before being transferred to the subsequent treatment stage.
6. The next stage of the proposed treatment process is biological treatment. Biological purification is commonly carried out using biofilters or activated sludge systems (aeration

tanks). While biofilters were traditionally employed in small and medium-sized settlements, activated sludge reactors are currently the preferred technology in large cities such as Shymkent due to their higher treatment efficiency and operational capacity. In the proposed technological scheme, wastewater undergoes biological treatment in aeration tanks, where organic pollutants are biodegraded by activated sludge microorganisms under aerobic conditions.

7. In the final stage of the treatment process, the treated wastewater enters an airlift chamber. An airlift chamber is a pneumatic device used in aeration systems to transport liquid or activated sludge by means of compressed air. This process enables the recirculation of activated sludge back into the biological treatment unit while simultaneously facilitating the removal of excess sludge and undesirable suspended solids from the treatment system, thereby improving the overall efficiency and stability of the wastewater treatment process.

CONCLUSIONS

The results of this study demonstrated that the biocoagulant derived from the bacterial strain *A. ferrooxidans Ach1* exhibits high efficiency in the treatment of organic wastewater. Microbiological investigations confirmed the strain's ability to oxidize ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which serves as the basis for the formation of biologically produced ferric sulfate and enhances the coagulation process.

Physicochemical analysis of municipal wastewater collected in Shymkent revealed that the concentrations of COD, phosphates, petroleum products, and oils substantially exceeded the maximum permissible concentrations, indicating a high degree of organic contamination and highlighting the need for the implementation of more efficient wastewater treatment technologies.

Laboratory experiments confirmed that the ferric sulfate-based biocoagulant produced by *A. ferrooxidans Ach1* effectively removed organic contaminants from wastewater. Based on these findings, an improved technological scheme was developed for the treatment of both municipal and petroleum refinery wastewater. The proposed process integrates mechanical, biocoagulation, and biological treatment into a single treatment train, thereby providing comprehensive removal of wastewater pollutants.

Furthermore, the proposed technological scheme enables the continuous production of biologically generated ferric sulfate in a bioreactor using *A. ferrooxidans Ach1*, demonstrating the potential to partially or completely replace conventional chemical coagulants. This approach reduces chemical reagent consumption, decreases sludge production, and improves the environmental sustainability of the wastewater treatment process.

Overall, the results confirm the scientific and practical feasibility of the proposed biocoagulation technology for the treatment of organic wastewater. Its implementation at full industrial scale has the potential to reduce the environmental impact of wastewater discharges, improve the operational efficiency of wastewater treatment facilities, and ensure compliance with environmental water quality standards through the production of treated effluent suitable for safe discharge.

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