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ADVANCED RESOURCE-EFFICIENT TECHNOLOGIES FOR CHROMIUM (VI) REMOVAL FROM INDUSTRIAL WASTEWATER: ANALYSIS AND REUSE POTENTIAL

Abstract. *The study addresses a scientific and practical challenge — investigating modern methods for the treatment of wastewater contaminated with hexavalent chromium (Cr(VI)), with a focus on the development of environmentally safe and resource-efficient technologies. The paper analyses key treatment approaches for galvanic wastewater, including chemical precipitation, electrocoagulation and galvanocoagulation, ion exchange, membrane filtration, sorption, and biological methods. The advantages, limitations, efficiency, and economic viability of each method are assessed. Special attention is given to technologies that remove Cr(VI) from wastewater and enable the recovery or reuse of extracted components in industrial processes. The prospects of applying natural and synthetic sorbents, ion-exchange processes for obtaining valuable products, and electrochemical and biological approaches as alternatives to conventional chemical methods are considered. The development of closed-loop technologies is substantiated as a promising direction to minimise the environmental impact of industrial effluents.*
Keywords: *wastewater, chromium (VI), water treatment, resource conservation, reuse, sorption methods, ion exchange, electrochemical treatment, biological treatment, waste utilisation, environmentally friendly technologies.*
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Introduction

In Ukraine, industry stands as the primary consumer of water resources, and the expansion of its capacities is accompanied by an increase in both water consumption and wastewater volumes. This intensifies the ecological burden on the environment, particularly due to toxic components present in effluents. Amid escalating environmental challenges, the implementation of effective industrial wastewater treatment technologies, especially in the context of developing resource-saving solutions, gains particular urgency. One of the priorities of modern environmental policy is to prevent the discharge of hazardous substances, including chromium (VI) components, which pose a threat to aquatic ecosystems and human health.

Chromium-containing components are the main harmful substances found in the wastewater of electroplating plants and industrial enterprises. These components exert an extremely negative impact on living organisms due to their cumulative and toxic properties, and they complicate the operation of natural and municipal wastewater treatment plants. Currently, most machine-building enterprises with electroplating production facilities face the problem of utilising electroplating waste sludge, particularly heavy metal ions, which are classified as hazardous waste of hazard classes 2-4 and significantly affect the state of the environment and human health (Genawi et al., 2020).

The presence of heavy metals in wastewater exerts a toxic effect on biological systems and the environment as a whole. A significant global challenge is the presence of chromium(VI) in industrial wastewater, as this substance is highly detrimental to animals due to its ability to generate reactive oxygen species in cells. Excessive chromium exposure affects the lungs and leads to respiratory disorders in humans (Bashir, 2021). Chromium-containing components hinder the vital activity of microorganisms and complicate the biochemical treatment process of wastewater. Therefore, the greatest danger lies in the high toxicity of these substances.

Numerous treatment processes for the removal of hexavalent chromium have been investigated and thoroughly reviewed. These include the use of natural absorbents; traditional chemical reduction methods; bioabsorption; the application of nanotechnology, and other techniques (Bashir, 2021; Shekhawat et al., 2015; Ying et al., 2020; Barakat, 2010; Gitet et al., 2013). Currently, experts estimate that thousands of tons of highly toxic heavy metals, such as zinc (3.3 thousand tons), nickel (2.4 thousand tons), and chromium (0.5 thousand tons), among others, enter water bodies annually with inadequately treated industrial wastewater, significantly complicating the ecological situation.

In light of these challenges, particular attention must be paid to the quality of wastewater treatment from highly toxic substances. Therefore, the aim of this work is to study the methodology and methods for treating wastewater to remove chromium(VI).

Analysis of Recent Research and Publications

Sorption technology stands out as one of the most promising methods for wastewater treatment, widely adopted in industrially developed countries. The effectiveness of the sorption method lies in its ability to remove heavy metals from large volumes of wastewater, regardless of pH levels, while simultaneously neutralising them. However, the complexity of sorptive removal of chromium(VI) compounds stems from their presence in aqueous solutions as anionic forms, which are poorly sorbed by conventional cation exchangers like clay minerals and zeolites. Specifically, the predominant forms of Cr(VI) in an aqueous environment are $HCrO_4^-$ and CrO_4^{2-}. $HCrO_4^-$ dominates at $pH < 4$, while chromate ions prevail at $pH > 9$ (Pylypenko & Spasonova, 2020; Homelia et al., 2012).

Another notable characteristic of hexavalent chromium compounds is their redox sensitivity. CrO_4^{2-} ions are easily reduced to their tri- or tetravalent states, even under relatively mild conditions. At low or neutral pH values, anionic forms of Cr(VI) act as powerful oxidizers (Barakat, 2010). Industrial pollution is the most common way for chromium (VI) to enter the environment, typically as a result of spills, improper storage, or disposal. It readily dissolves in water and is known to penetrate water sources, leach into groundwater, and enter the human body (Gitet et al., 2013). A well-documented case involved PG&E discharging approximately 370 million gallons of chromium-contaminated wastewater into water bodies near Hinkley, California, leading to significant groundwater contamination (Kennedy, 2003). This case vividly illustrates the need for not only effective removal of chromium (VI) from wastewater but also the implementation of technologies that enable its reuse in the production cycle. This approach helps reduce the volume of toxic sludge, lowers waste disposal costs, and preserves chromium as a valuable resource. In the context of rising raw material costs and a global shift toward a circular economy, the regeneration and return of chromium to the technological process is not only environmentally sound but also economically beneficial.

Despite the variety of modern approaches to heavy metal wastewater treatment – including reagent, ion exchange, electrochemical, and membrane methods – most remain highly specialized, limited in terms of economic efficiency, or lack environmental universality. The presence of chromium(VI) in electroplating effluents not only poses a distinct toxic threat but can also complicate the removal processes of other pollutants. A review of scientific works (Pylypenko & Spasonova, 2020; Homelia et al., 2012; Vukĉević et al., 2014; Liniucheva et al., 2017; Jung et al., 2013; Gorshkova et al., 2015; Suvorin et al., 2019) allows for a systematic classification of current treatment methods for such effluents and an evaluation of their effectiveness in complex matrices containing Cr(VI).

This study aims to analyze methods and methodologies for wastewater treatment to remove chromium(VI), with a particular emphasis on technologies that allow for the processing and reuse of extracted substances in production processes, contributing to the creation of environmentally friendly and resource-efficient technologies.

Elucidating the Core Research Material

Chromium(VI) is an elemental compound formed during industrial processes. This heavy metal is classified as a human carcinogen. Its penetration into the body can occur through inhalation, ingestion, and skin contact (Ying et al., 2015). Chromium most commonly exists in its trivalent (Cr(III)) and hexavalent (Cr(VI)) states. Notably, Chromium(VI) is known to be toxic to animals, capable of causing dermatitis, lung cancer, kidney and stomach damage, and respiratory and eye irritation (Shekhawat et al., 2012).

Chromium possesses multiple oxidation states, each with a unique set of properties. For instance, the trivalent state of chromium, Cr(III), is essential for carbohydrate metabolism in humans (Kennedy, 2003). Conversely, hexavalent chromium, Cr(VI), is considered toxic. Cr(VI) is one hundred times more toxic than Cr(III) and is also more soluble in water. It acts as a strong oxidizer, capable of releasing free radicals that exert carcinogenic effects on cells. Cr(VI) typically forms compounds with other elements, such as iron(II) chromite ($FeCr_2O_4$) (Pylypenko & Spasonova, 2020).

Currently, various methods have been developed and are employed for the removal of Chromium(VI) from wastewater. These methods include reduction of chromium(VI) to chromium(III), electro- and galvanocoagulation, ion exchange, membrane, sorption, and biological methods (Bashir, 2021; Shekhawat et al., 2015; Ying et al., 2020; Barakat, 2010; Gitet et al., 2013). However, almost all of these approaches involve the use of various chemical reagents. Following their application, the salt content of the treated water increases, often rendering it unsuitable for discharge into the environment and necessitating additional purification steps (Pylypenko & Spasonova, 2020; Vukĉević et al., 2014).

The traditional method for treating wastewater contaminated with hexavalent chromium relies on its reduction to trivalent chromium, followed by precipitation as hydroxide in an alkaline environment. Common reducing agents include sulfur dioxide, sodium sulfite, sodium bisulfite, and hydrazine. Additionally, activated carbon, ferrous sulfate, hydrogen, sulfur dioxide, and organic waste materials can also serve as reductants (Homelia et al., 2012). Reagent-based treatment of effluents is carried out in both continuous and batch-mode installations. The upper limit for batch-mode applications is typically defined by a capacity of up to 20 m^3/hour.

In practice, sodium sulfite (Na_2SO) solutions are effectively used in an acidic environment for the reduction of chromium (VI) to chromium (III). According to research (Beukes et al., 1999), the optimal pH range for this reaction is 2-5, with the reduction rate significantly decreasing as the pH increases to 6 and above. Sulfite reacts with Cr(VI) according to the following equations:

$$2HCrO_4^- + 4HSO_3^- + 6H^+ \rightarrow 2Cr^{3+} + 2SO_4^{2-} + S_2O_6^{2-} + 6H_2O;$$
$$2HCrO_4^- + 3HSO_3^- + 5H^+ \rightarrow 2Cr^{3+} + 3SO_4^{2-} + 5H_2O.$$

Research indicates that to achieve a 95% reduction in Cr(VI) concentration, the concentration of sulfite must be five times greater than the initial Cr(VI) concentration. However, an excess of S(IV) can lead to the formation of $S_2O_6^{2-}$, which may necessitate additional treatment stages for secondary products. Experiments utilizing ferromolybdenum production dust demonstrated that sodium sulfite is effective for Cr(VI) concentrations up to 26 mg/L, provided the solution's pH is strictly controlled (Beukes et al., 1999).

Coagulation is the process where dispersed particles agglomerate due to their interaction and combine into larger aggregates. Coagulation can occur spontaneously under the influence of chemical and physical processes. However, in wastewater treatment, coagulation is typically induced by adding specialized substances called coagulants (Barakat, 2010). Coagulants, when introduced into water, form rapidly settling flocs of metal oxide hydrates under the force of gravity.

For the treatment of chromium-containing wastewater, aluminium and iron salts are commonly used as coagulants. The most widely used coagulant is aluminium sulfate, $Al_2(SO_4)_3 \cdot 18H_2O$, which is effective within a pH range of 5 - 7.5. Studies have shown that using mixtures of $Al_2(SO_4)_3$ and $FeCl_3$ in ratios of 1:1 or 1:2 significantly increases the settling rate of flocs and reduces Cr(VI) concentrations to acceptable levels (Bashir, 2021).

Sodium aluminate ($NaAlO_2$) and aluminium oxychloride ($Al_3(OH)_5Cl$) are employed for treating weakly alkaline waters due to their lower acidity and ability to accelerate the coagulation process. Their combined use allows for increased sludge density and expands the effective pH range (Homelia et al., 2012).

Iron salts, particularly $Fe_2(SO_4)_3$ and $FeCl_2$, demonstrate high coagulation efficiency at low water temperatures and across a broad pH range (6 - 9 for Fe^{3+} and 9.5 and above for Fe^{2+}) (Bashir,2021). Ferric chloride is typically used at 10-15% and $Al_2(SO_4)_3$ not only facilitates Cr(VI) removal but also enables the recovery of Cr(III) for subsequent industrial reuse (Homelia et al., 2012).

Furthermore, natural flocculants (e.g., starch, cellulose) and synthetic polymers are utilized to neutralize chromium. These substances accelerate particle aggregation and promote the formation of dense flocs (Lazarieva et al., 2019; Bashir, 2021).

The high toxicity of sulfide-alkaline solutions and the impossibility of their direct discharge into water bodies and soils necessitate the research and development of alternative and more effective technologies for their processing and neutralization.

One method that prevents chromate ions from entering municipal sewers is ion exchange (Homelia et al., 2004). However, the implementation of ion exchange technology leads to the accumulation of regeneration solutions, the disposal of which results in the formation of toxic sludges and the loss of valuable components. In this context, the selective removal of Cr(VI) is crucial, as it avoids its reduction to Cr(III) and subsequent change in oxidation state. Nevertheless, when using membrane methods, Cr(VI), being a strong oxidizer, can cause damage to polymeric membranes, limiting their application. Thus, the issue of effective disposal of regeneration solutions remains relevant, as Cr(VI) can be present in concentrated form as chromate or dichromate, requiring further processing and disposal methods.

During the desorption of chromium (VI) from anion exchangers, regeneration solutions are formed, the composition of which depends on the chosen type of regeneration. For example, when alkalis are used, solutions containing chromium (VI) in concentrations of about 10 g/dm^3 are produced, with an excess of NaOH potentially reaching about 10 g/dm^3. Solutions formed using formic acid in the reductive regeneration process should be evaporated in a rotary evaporator. This process distils off water with excess formic acid, and this solution is then reused for ionite regeneration. The residue is chromium formate, which is a valuable substance (Table 1). From chromium formate, metallic chromium can be obtained in a reducing environment. This product is used in the production of metal powders and in applying metallic coatings to surfaces (Homelia et al., 2004).

The reviewed method for processing and utilizing chromium-containing regeneration solutions enables the creation of environmentally friendly technologies and the isolation of chromates as valuable products (Homelia et al., 2004).

When dealing with high concentrations of heavy metals in wastewater, electrochemical treatment methods are often employed. These methods are advantageous as they typically do not require additional reagents and can be fully automated. In most cases, electrochemical methods are environmentally clean, eliminating the "secondary" contamination of water with anionic and cationic residues that are characteristic of reagent-based approaches.

Table 1. Obtaining Chromium Formates During Reductive Regeneration (Homelia et al., 2004)

Composition of Regeneration Solution	Reagent Dose, g	Mass of Sorbed Chromium (VI), g	Mass of $Cr(HC(O)O^-)_3$, g	Yield $Cr(HC(O)O^-)_3$, g
$C_3H_8O_3$, HC(O)OH	1:20	2,01	6,5	96,3
$C_3H_8O_3$, HC(O)OH	1:10	1,94	6,6	97,1
$C_3H_8O_3$, HC(O)OH	1:1	2,01	6,7	96,7

A patented electrochemical wastewater treatment technology exists for removing chromium-containing compounds. During this purification process, all chromates convert into insoluble $Cr(OH)_3$ compounds. However, a drawback of this method is the need for complex equipment, specifically an electrolyzer with lead electrodes, and increased energy consumption.

A combined electrocoagulation-electroflotation process has been developed to reduce Cr(VI) concentrations to below 0.5 mg/L without the need for filtration (Gao et al., 2005). This process involves the preliminary reduction of Cr^{6+} to Cr^{3+}, followed by the coagulation and flotation of $Cr(OH)_3$ and $Fe(OH)_3$ sludge using air bubbles. This method can decrease energy consumption to 1 kWh/m³ of water at an electrical load of 2.5 F/m³ of water. Nevertheless, a challenge with this technology is the removal of fine flocs, which may require additional purification steps.

Electrochemical methods for neutralizing or regenerating chromium-containing effluents are categorized into several types: electrolysis without a diaphragm, membrane electrolysis with one or more membranes, electrocoagulation and galvanocoagulation, electroflocculation, and electroflotation (Pylypenko & Spasonova, 2020).

It's worth noting that electrodeposition of metals from wastewater addresses several critical objectives, particularly technical-economic (by returning metals to production) and environmental ones, which draws significant attention. However, the use of electrochemical methods faces several limitations. The efficiency of wastewater purification during electrochemical treatment is influenced by various physicochemical, electrical, and hydrodynamic factors, including the wastewater's salt composition, temperature, the composition of added electrolyte, the flow rate of water in the inter-electrode space, and current density (Liniucheva et al., 2017).

While electrochemical methods offer potential for wastewater treatment, they require precise adherence to influent parameters, which is often challenging to achieve under real industrial conditions. Additionally, the presence of extraneous ions in the wastewater can interfere with the reduction process.

Sorption methods are highly effective and prevent the formation of mixed sludges from spent solutions. Among these, the use of powdered activated carbon (PAC) is particularly notable. It not only reduces Cr(VI) concentrations by reducing it to Cr(III) but also allows for subsequent adsorption of Cr(III) onto the PAC itself. A study (Shinde et al., 2018) found that this method can achieve purification levels below 2 ppm without generating sludge, making it a promising option for industrial-scale application. Key parameters for selecting a material for this method include its sorption qualities, porosity, and cost-effectiveness. Carbon sorbents (Vukĉević et al., 2014), iron compounds (Jung et al., 2013), and various natural biomaterials are used as sorbents for treating spent chromium-containing solutions. The advantages of the sorption method include:

- purification to the maximum permissible concentration (MPC) requirements;
- the possibility of recovering sorbed substances;
- the potential to return treated water to production after pH adjustment (Pylypenko & Spasonova, 2020).

The main factors influencing the effectiveness of sorption (the sorption capacity of the anion exchanger) are pH, contact time, and chromium concentration. Benefits of this method include its extremely low sensitivity to the initial contaminant content, the ability to discharge treated wastewater to municipal aeration stations, and the option to discharge treated wastewater into water bodies for cultural and domestic use (with additional purification using electrodialysis or ion-exchange filters).

Research (Homelia et al., 2002) has demonstrated that the sorption capacity of the anion exchanger AV-17-8 is maximized in the pH range of 2-6 when using chromic acid solutions. At pH 7-13, the ion exchanger's capacity decreases by a factor of 2 or more. The distribution coefficient reaches its peak value at pH 2 and a chromium concentration of 10 g/L. At low chromium concentrations (up to 1 g/L) in potassium dichromate solutions, the distribution coefficient in an alkaline environment differs little from its values in a neutral environment. This particular ion exchanger can effectively remove chromate anions from environments with pH up to 12, at chromate concentrations up to 1 g/L.

In establishing the physicochemical characteristics of purifying natural waters from chromium(VI) contamination using composite sorbents based on clay minerals modified with nanoscale iron, the influence of key factors on the sorption process was investigated. These factors included the dispersity of sorbent particles, the ratio of main components within the composite sorbent, and the pH of the aqueous medium. The effectiveness of chromium removal by modified silicate materials was compared with the sorption capacity of synthesized nanoscale Fe^0 dispersions. To determine the optimal conditions for chromium sorption by iron-containing materials, the impact of sorbent-solution contact time was studied ($I = 0.01$, $C_{Cr(VI)} = 1000$ µmol/dm^3).

The obtained data indicate that the maximum sorption capacity for chromium by the studied Fe^0 samples consistently increases with increasing dispersity. To enhance the dispersity of nanoscale Fe^0, it was synthesized in the presence of montmorillonite, and the physicochemical characteristics of its sorption capacity towards metal anions were investigated (Pylypenko & Spasonova, 2020).

An alternative to using chemical reagents is the biological treatment method. This approach is based on the natural self-purification capacity of water bodies and the ability of plants and microorganisms to accumulate heavy metals. The high accumulative capacity of microalgae regarding heavy metals creates prospects for their use in wastewater treatment. Existing biotechnology experience indicates that accumulation efficiency can reach up to 95% (Gorshkova et al., 2015).

Bacteria capable of reducing Cr^{6+} to Cr^{3+} include species from the genera *Pseudomonas*, *Aeromonas*, and *Escherichia*. These bacteria can tolerate Cr^{6+} ion concentrations exceeding 200 mg/L, with a reduction time of 1-3 days. This time increases to 20 and 60 days, respectively, when the initial concentration of chromium compounds rises to 350 and 500 mg/L (Petruk et al., 2013; Homelia & Sagaidak, 2004).

Common disadvantages of biological methods for neutralizing spent solutions containing chromium(VI) ions include the sensitivity of microorganisms to changes in wastewater composition and increased concentrations of toxic components; significant land area requirements; insufficient treatment efficiency; and the lengthy duration of the technological process. Moreover, after treatment, chromium accumulates within the biomass, which subsequently needs to be disposed of, but now in the form of biomaterial (Petruk et al., 2013; Homelia & Sagaidak, 2004).

Thus, modern treatment methods for hexavalent chromium removal have been investigated and thoroughly reviewed. These include the use of natural sorbents, traditional chemical reduction, ion exchange, electrochemical, and biological methods. Table 2 provides a comparative analysis of the discussed treatment methods, highlighting their main advantages and disadvantages.

Conclusions and Prospects for Further Research

In conclusion, the disposal of spent chromium-containing solutions can be achieved through numerous methods. The reagent method is currently the most widespread practice in Ukraine for neutralizing electroplating wastewater. Its primary advantage lies in its extremely low sensitivity to the initial contaminant content, while its main drawback is the high residual salt content of the treated water, necessitating further purification.

Table 2. Advantages and Disadvantages of Wastewater Treatment Methods for Cr(VI)

Method	Essence of Method / Method Principle	Advantages	Disadvantages
Reagent Method	Involves converting chromium(VI) ions to the trivalent state and precipitating them as an insoluble product. The reagent method can be considered two-stage; however, after obtaining insoluble products, the pulp undergoes several more processing steps: settling and filtration through a filter press to produce sludge.	It is relatively simple to implement and does not require specialized equipment. It allows for operation across a wide range of effluent parameters (qualitative and quantitative composition, pH, etc.). Most large machine-building factories utilize this specific wastewater treatment method.	The resulting sludges are characterized not only by a complex composition but also by an amorphous gel-like structure. Subsequent filtration and drying pose a significant technical and economic problem for enterprises.
Ion-Exchange Methods	Enable the purification of spent solutions from both chromium(III) and chromium(VI) ions, allowing for the treatment of large volumes of solutions (up to hundreds of m^3/hour).	Require relatively low electricity consumption, with the possibility of full process automation.	Demand preliminary reagent treatment of spent solutions to separate mixed effluents and entail significant costs for ionite acquisition. There is also the problem of eluates, which must be further processed into disposable substances. Without addressing the problem of eluate disposal, ion-exchange purification leads to an almost threefold increase in the total amount of salt discharges.
Sorption Treatment	Highly effective and among the most environmentally friendly methods. Key parameters for material selection include sorption qualities, porosity, and cost-effectiveness. Carbon sorbents, iron compounds, and various natural biomaterials are used as sorbents for neutralizing spent chromium-containing solutions.	Purification to maximum permissible concentration (MPC) requirements; possibility of recovering sorbed substances; possibility of returning treated water to production after pH adjustment.	Low productivity of sorption units; natural sorbents are applicable for a limited range of impurities and their concentrations; cumbersome equipment; material operating limitations based on the pH range of the source water; complexity of regeneration.

Method	Essence of Method / Method Principle	Advantages	Disadvantages
Electro-chemical Methods	Chromium participates in reactions at the electrodes, primarily involving the deactivation of hexavalent chromium by its reduction to the trivalent state at the cathode. To prevent the reverse oxidation reaction at the anode, membranes and diaphragms can be used.	Speed and completeness of reduction. No sludge is formed during electrolysis.	The process requires precise adherence to the parameters of the incoming effluents, which is very difficult to achieve under real production conditions. Additionally, the effluent composition may include extraneous ions that interfere with the reduction process. Electrochemical reduction is rarely applied in real electroplating industries due to the complexity of the equipment and the overall high cost of the process.
Electro- and Galvano-coagulation Methods	In both methods, iron is first dissolved. The resulting Fe^{2+} ions then reduce Cr^{6+} to Cr^{3+}, leading to the subsequent formation of $Cr(OH)_3$.	Speed and completeness of reduction. Besides iron anodes, aluminium anodes can also be used.	The disadvantages include the use of large quantities of acid and alkali, and the formation of a significant amount of practically unusable sludge, which is a mixture of iron and chromium hydroxides. During the operation of electrocoagulators, clogging of the inter-electrode space is observed, necessitating constant cleaning with scrapers. When maintaining galvano-coagulators, it's necessary to constantly maintain the ratio of steel chips to coke or steel chips to copper chips.
Membrane Methods	Suitable for treating low-concentration spent solutions, as high-concentration effluents quickly damage membranes, and the purification quality in such cases is often low.	Membrane methods prove effective for regenerating components from spent solutions and certain types of rinse waters after technological operations.	In real-world conditions, similar to electrochemical treatment methods, maintaining precisely defined effluent parameters is difficult. These methods are also quite expensive to operate. Membranes are rather scarce and sensitive to changes in the techno-logical characteristics of spent solutions.

Method	Essence of Method / Method Principle	Advantages	Disadvantages
Biological Methods	An alternative to using chemical reagents. This method is based on the self-purification of water bodies and the ability of plants and microorganisms to accumulate heavy metals. The high accumulative capacity of microalgae regarding heavy metals creates prospects for their use in wastewater treatment.	Low energy consumption, absence of secondary water pollution, relatively low operating costs, and the ability to meet stringent discharge standards. Existing biotechnology experience shows that accumulation efficiency can reach up to 95%.	Sensitivity of microorganisms to changes in wastewater composition and increased concentrations of toxic components; significant land area requirements; insufficient treatment effect; and lengthy technological processes. Additionally, after purification, chromium accumulates within the biomass, which then requires further disposal, but now in the form of a biomaterial.

The high toxicity of sulfide-alkaline solutions and the impossibility of their direct discharge into water bodies and soils compel the research and development of alternative, resource-saving technologies that generate minimal waste.

An analysis of modern treatment methods reveals that the sorption method is the most optimal, considering both technical-economic indicators and environmental criteria. This method can significantly reduce the concentration of chromium ions, even from solutions where ion concentrations are low and other methods are nearly ineffective. Natural aluminosilicates such as zeolites, bentonite clays, and montmorillonite minerals exhibit good sorption properties.

Detailed studies have shown that composite sorbents display better sorption properties for chromium than pure nanoscale iron. This is attributed to the inclusion of clay minerals during synthesis, which enhances the sorption capacity of the resulting composites by increasing their dispersity due to reduced agglomeration of nanoscale iron particles, thereby increasing the specific surface area of the modified samples. Prospects for further research include the search for and testing of new sorbents derived from more accessible natural materials.

To enhance environmental safety, significant attention must be paid to investigating the ion-exchange method for processing and utilizing chromium-containing regeneration solutions. This method allows for the creation of environmentally friendly technologies and the isolation of chromates as valuable products, enabling their return to technological processes.

Thus, the results of the analysis indicate that electrocoagulation using hybrid Fe-Al electrodes is a highly effective method for reducing Cr(VI) concentrations to below 0.3 mg/L, achieving 97% removal (Gao et al., 2005). At the same time, despite the significant efficiency of Cr(VI) removal, the regeneration of chromium in the form of $Cr(OH)_3$ is limited due to the complexity of its subsequent extraction and sludge processing. This underscores the importance of further research aimed at improving technological solutions that not only remove chromium from wastewater but also ensure its effective reuse in production processes, fostering a transition to environmentally clean and resource-efficient technologies.

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ПЕРЕДОВІ РЕСУРСОЕФЕКТИВНІ ТЕХНОЛОГІЇ ВИДАЛЕННЯ ХРОМУ (VI) З ПРОМИСЛОВИХ СТІЧНИХ ВОД: АНАЛІЗ ТА ПОТЕНЦІАЛ ПОВТОРНОГО ВИКОРИСТАННЯ

Анотація. Дослідження стосується наукового та практичного завдання – дослідження сучасних методів очищення стічних вод, забруднених шестивалентним хромом (Cr(VI)), з акцентом на розробку екологічно безпечних та ресурсоефективних технологій. У статті аналізуються ключові підходи до очищення гальванічних стічних вод, включаючи хімічне осадження, електрокоагуляцію та гальванокоагуляцію, іонний обмін, мембранну фільтрацію, сорбцію та біологічні методи. Оцінено переваги, обмеження, ефективність та економічну доцільність кожного методу. Особлива увага приділяється технологіям, що видаляють Cr(VI) зі стічних вод та дозволяють відновлювати або повторно використовувати екстраговані компоненти в промислових процесах. Розглянуто перспективи застосування природних та синтетичних сорбентів, процесів іонного обміну для отримання цінних продуктів, а також електрохімічних та біологічних підходів як альтернатив традиційним хімічним методам. Обґрунтовано розвиток технологій замкнутого циклу як перспективний напрямок мінімізації впливу промислових стічних вод на навколишнє середовище.

Ключові слова: стічні води, хром (VI), очищення води, ресурсозбереження, повторне використання, сорбційні методи, іонний обмін, електрохімічне очищення, біологічне очищення, утилізація відходів, екологічно чисті технології.

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