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RECOVERY OF CHROMIUM FROM WASTEWATER INTO PRODUCTION: ANALYSIS OF MODERN TECHNOLOGIES AND APPLICATION PROSPECTS

Serhii POROSHENKO, Oleksandr KHOKHOTVA
Igor Sikorsky Kyiv Polytechnic Institute
Beresteyskyi Ave., 37, Kyiv 03056, Ukraine
e-mail: s.poroshenko@kpi.ua

Abstract
This study is dedicated to analysing modern resource-efficient methods for treating industrial wastewater containing chromium compounds, with a focus on technologies that enable the reintegration of recovered chromium into the production cycle. The work examines ion exchange, sorption, electrodialysis, and membrane processes, which remove chromium from effluents and convert it into forms suitable for reuse in industrial operations. The paper outlines future research prospects aimed at improving technologies for the concentration and regeneration of chromium compounds for integration into closed-loop production systems.

Keywords: *wastewater, chromium (VI), water purification, resource conservation, secondary use, environmentally friendly technologies.*

The problem of industrial wastewater contamination with chromium compounds remains highly relevant due to the high toxicity of hexavalent chromium (Cr(VI)) and its ability to accumulate in the environment [1].

Sources of chromium-containing effluents include electroplating workshops (chromium plating), leather production (chrome tanning), pigment manufacturing, and others. Traditional treatment methods for such effluents are aimed at detoxifying Cr(VI) by reducing it to the less toxic trivalent chromium (Cr(III)), followed by chemical precipitation of the insoluble hydroxide $Cr(OH)_3$ [2]. Although these reagent-based methods effectively reduce chromium concentrations in water, they generate large amounts of waste — either toxic sludge or sulfide-alkaline solutions — which cannot be discharged directly into the environment. Therefore, there is a pressing need to implement resource-efficient technologies that minimize waste generation and enable the recovery of extracted chromium as a valuable raw material for reuse in the production cycle.

Chemical Precipitation and Coagulation. Reagent-based precipitation (through the addition of alkalis, sulfides, etc.) is the most widespread method for treating chromium-containing wastewater due to its simplicity and low sensitivity to fluctuations in water composition [2]. Cr(VI) is typically reduced to Cr(III) (e.g., using sulfite, $FeSO_4$, or via catalytic reduction with a TiO_2-palladium catalyst [6]) and then precipitated as $Cr(OH)_3$. The main drawbacks of this method are the high salt content in the treated water and the generation of toxic sludge, which requires further disposal. Electrochemical coagulation using soluble anodes (Fe, Al) enables simultaneous reduction of Cr(VI) to Cr(III) at the cathode and precipitation of chromium hydroxide along with metal hydroxides from the anodes. However, chromium recovery for reuse in production is challenging with these technologies: the resulting $Cr(OH)_3$ sludge requires additional processing [2].

Sorption Methods. Chromium adsorption on solid sorbents is characterized by versatility and high efficiency, even at low pollutant concentrations. Natural aluminosilicates (such as zeolites, bentonites, and montmorillonites) and modified materials based on them are being studied as sorbents. Nanomaterials with a high specific surface area also show great promise. The adsorbed chromium can be desorbed from the sorbent by acid treatment, and the resulting concentrated chromium solution can be feasibly returned to the production cycle [3].

Ion Exchange. Ion-exchange resins are capable of selectively removing chromate ions $Cr(VI)O_4^{2-}$ from solutions, accumulating chromium in a concentrated regeneration solution. The use of anion-exchange resins is effective for extracting Cr(VI); further treatment of the saturated regeneration solution can yield marketable reagents — chromium compounds suitable for electroplating or leather tanning applications [5].

Membrane Technologies and Electrodialysis. Ultrafiltration, nanofiltration, and reverse osmosis processes enable the separation of the wastewater stream into purified water and a chromium-enriched concentrate. Reverse osmosis is considered the most promising method at the final stage of treatment [4]. The resulting concentrate, containing significant amounts of Cr(III), can be directly returned to the electroplating process. Additionally, electrodialysis allows the concentration of chromium compounds into forms suitable for technological processes, particularly chromates or dichromates, which can be reused in production [7].

Biological Methods. Microorganisms (such as bacteria and fungi) are capable of reducing Cr(VI) to Cr(III) through metabolic processes and can also accumulate chromium within their cells. The resulting biomass enriched with chromium requires subsequent disposal [8].

The analysis demonstrates that the implementation of closed-loop wastewater treatment systems with chromium recovery for reuse in production is a promising direction in the development of resource-saving technologies. Methods such as electrodialysis, electrochemical resin regeneration, and reverse osmosis not only reduce reagent consumption but also enable the reuse of chromium in industrial processes, aligning with the principles of the circular economy.

However, to achieve maximum efficiency from the implementation of such technologies, further research is needed to improve methods for recovering chromium in forms suitable for technological use. In particular, the development of new materials for ion exchange and sorption holds great promise, as these could not only extract chromium but also convert it into forms applicable in industrial settings. Optimizing regeneration processes for sorbents and ion-exchange resins is also important to minimize the generation of secondary waste. Thus, future research should focus on the integration of technologies that combine purification, concentration, and recycling of chromium into the production cycle.

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ПОВЕРНЕННЯ ХРОМУ ЗІ СТІЧНИХ ВОД У ВИРОБНИЦТВО: АНАЛІЗ СУЧАСНИХ ТЕХНОЛОГІЙ ТА ПЕРСПЕКТИВИ ЇХ ЗАСТОСУВАННЯ

Сергій ПОРОШЕНКО
Київський політехнічний інститут імені Ігоря Сікорського
пр. Берестейський, 37, м. Київ, 03056, Україна
https://orcid.org/0009-0001-8258-8033

Олександр ХОХОТВА
Київський політехнічний інститут імені Ігоря Сікорського
пр. Берестейський, 37, м. Київ, 03056, Україна
https://orcid.org/0000-0002-2607-9242

Анотація

Дана робота присвячена аналізу сучасних ресурсозберігаючих методів очищення промислових стічних вод від сполук хрому з акцентом на технологіях, що дозволяють повернути вилучений хром у виробничий цикл. Розглянуто методи іонного обміну, сорбції, електродіалізу та мембранних процесів, що сприяють не лише видаленню хрому зі стоків, але й його перетворенню у форми, придатні для повернення у виробничий цикл. Окреслено перспективи подальших досліджень, спрямованих на вдосконалення технологій концентрування та регенерації хромових сполук для інтеграції у замкнені цикли виробництва.

Ключові слова: стічні води, хром (VI), очищення води, ресурсозбереження, вторинне використання, екологічно чисті технології.