JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Treatment of Cr(VI)-Containing Industrial Effluents: From Speciation and Reduction Mechanisms to Integrated, Sustainable, and Industrially Scalable Processes

Antonio Clareti Pereira, Ph.D.
Department of Graduate Program in Materials Engineering
Federal University of Ouro Preto (UFOP)
Ouro Preto, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Hexavalent chromium, Cr(VI), remains a high-priority contaminant in industrial water management because its hazard depends not only on total chromium concentration but also on oxidation state, aqueous speciation, matrix composition, and the stability of downstream residues. This critical review evaluates Cr(VI)-containing effluents from electroplating, tanning, metallurgical, chemical, mineral-processing, chromite-processing, cement, and related industries, emphasizing the distinction between Cr(VI) reduction and true chromium removal. Conventional reduction–neutralization–precipitation is compared with adsorption and ion exchange, membrane and electrochemical processes, zero-valent iron, photocatalysis, biological treatment, permeable reactive barriers, and integrated hybrid systems. The analysis prioritizes evidence from real wastewaters, continuous flow, pilot testing, regeneration studies, chromium recovery, residue stability, and techno-economic or life-cycle assessment, rather than maximum removal percentages measured in idealized single-solute batch tests. A six-level Cr(VI) Treatment Evidence Ladder is proposed to separate proof-of-concept performance from industrially transferable evidence. The review shows that high apparent Cr(VI) disappearance can mask incomplete total-chromium removal, transfer of chromium to unstable solids, concentrate generation, or sensitivity to competing ions. The strongest future pathway is therefore speciation-resolved and mass-balance-based process integration that couples selective reduction or capture with chromium recovery, low-sludge polishing, water reuse, and explicit evaluation of cost, scale, and residual risk.

Keywords: hexavalent chromium; industrial effluents; chromium speciation; wastewater treatment; chromium recovery; process integration

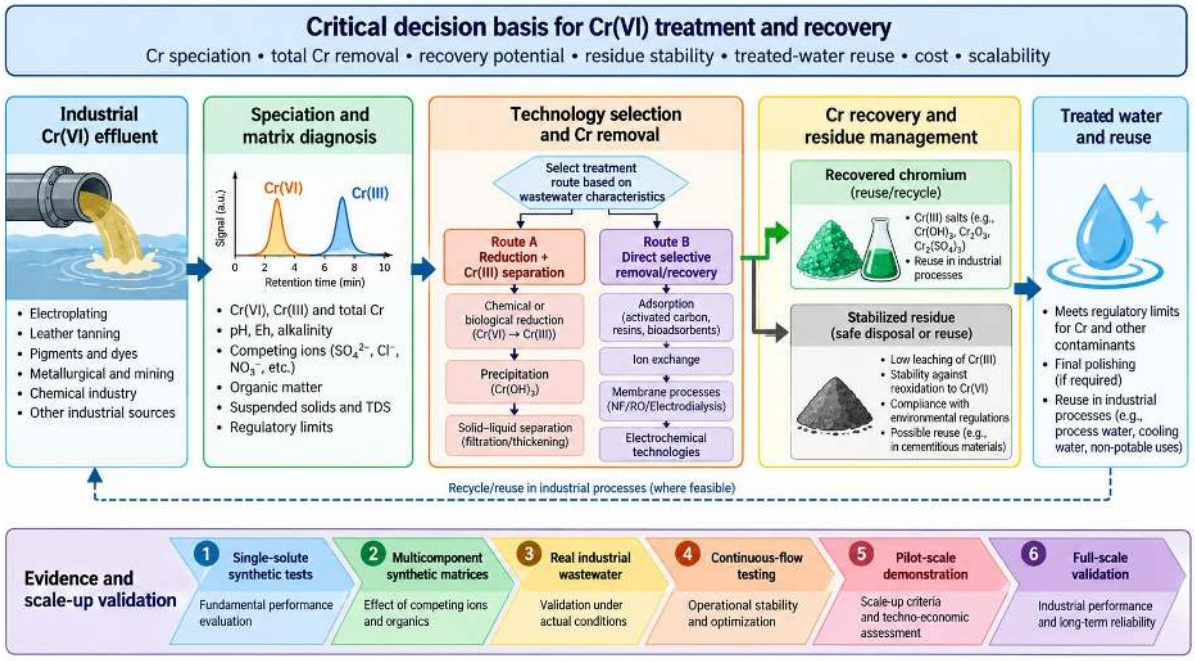
Highlights

- Distinguishes Cr(VI) reduction from verified total-chromium removal.
- Prioritizes real-effluent, continuous-flow, pilot, and industrial evidence.
- Integrates recovery, residue stability, water reuse, TEA, LCA, and scale validation.
- Proposes a six-level Cr(VI) Treatment Evidence Ladder for technology appraisal.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Graphical abstract



Note. Developed by the author as a conceptual synthesis of the critical framework proposed in this review.

1. Introduction

1.1. Industrial relevance and the persistent Cr(VI) problem

Chromium is indispensable to corrosion-resistant alloys, surface finishing, pigments, refractory materials, leather processing, and several chemical and metallurgical operations. The same redox versatility that gives chromium technological value complicates wastewater control: Cr(III) and Cr(VI) differ sharply in charge, mobility, sorption behavior, toxicity, and treatability. Consequently, an analytical result reported only as total chromium cannot reveal the treatment mechanism, the residual hazard, or the likelihood of remobilization. Current literature therefore supports a speciation-centered interpretation of chromium pollution and treatment rather than a single concentration-based view (Alvarez et al., 2021; Islam et al., 2022; Ukhurebor et al., 2021).

The central distinction used throughout this review is that Cr(VI) disappearance is not synonymous with chromium removal. A reductive step can convert chromate or dichromate

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

into Cr(III) while leaving the newly formed cation dissolved, colloidal, or weakly bound to solids. Conversely, a separation process can remove Cr(VI) without detoxifying a concentrated reject stream. An industrially defensible process must therefore demonstrate both redox conversion and chromium mass transfer, together with the stability and disposition of residues, regenerants, and concentrates.

1.2. Scope, critical-review approach, and organization

This review draws on a working corpus of 145 bibliographic entries selected for direct relevance to Cr(VI) sources, speciation, toxicology, chemical treatment, adsorption and ion exchange, membrane and electrochemical separation, advanced reduction, biological remediation, real-wastewater matrix effects, chromium recovery, circularity, scale-up, cost, and environmental assessment. The corpus should be understood as a critical narrative collection rather than a systematically reproducible search: database queries, screening counts, and study-level quality appraisals were not documented in the source manuscript. Literature is interpreted through an evidence hierarchy that gives progressively greater weight to multicomponent matrices, real wastewater, continuous flow, pilot operation, and full-scale performance. The approach is critical rather than cataloging: reported removal percentages are considered meaningful only when pH, speciation, total chromium, competing ions, dosage, hydraulic conditions, regeneration, residues, and scale are sufficiently described.

Literature discovery and evidence selection. The review is a critical narrative synthesis of 145 bibliographic entries. The surviving source documentation does not establish the exact databases consulted, final search date, original Boolean strings, duplicate-screening counts, or prospective eligibility decisions; these details are therefore not reconstructed as if prospectively recorded. Eligible evidence addressed industrial chromium sources, aqueous speciation, toxicity, conventional and advanced treatment, real-effluent applicability, regeneration, residue fate, recovery, process economics, and scale-up. Primary experimental studies were interpreted alongside critical reviews and foundational mechanistic sources, without treating secondary synthesis as independent experimental confirmation. Citation-chaining could not be independently documented for the original collection. Accordingly, this article makes no claim to systematic-review coverage or PRISMA-compliant selection. The evidence comparisons are

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

qualitative, mechanism-aware, and conditional on the reported matrix, analytical basis, operation mode, and fate of chromium-containing side streams.

The manuscript is organized so that source characteristics in Table 1 are connected to aqueous speciation in Figure 1, process metrics in Table 2, membrane and electrochemical contaminant flows in Figure 2, matrix effects in Table 3, integrated recovery and water-reuse pathways in Figure 3, comparative technology performance in Table 4, and the evidence hierarchy in Figure 4. This explicit linkage between the figures and tables is intended to prevent isolated interpretation of technology performance and to keep the discussion anchored to industrial decision variables.

The six-level Evidence Ladder introduced in Section 12.3 is an author-developed translational evidence framework for comparative interpretation, not a validated methodological quality scale, formal risk-of-bias instrument, or substitute for the standard nine-level technology readiness level (TRL) system.

2. Sources, occurrence, and characteristics of Cr(VI)-containing effluents

2.1. Electroplating, surface finishing, tanning, and chemical manufacture

Electroplating and surface finishing produce some of the most treatment-relevant Cr(VI) streams because chromium can occur at high concentration in relatively low-volume rinses, while mixed rinses contain Ni, Zn, Cu, Fe, surfactants, complexants, chloride, sulfate, and variable acidity. Segregating concentrated chromate-bearing streams enables selective recovery; commingling them with other metal-bearing waters generally increases reagent demand, sludge volume, and separation complexity. Recent studies on electroplating wastewaters and sludges illustrate both the opportunity for selective chromium management and the penalty imposed by mixed-metal matrices (Bratovcic et al., 2022; Cheng et al., 2021; Du et al., 2023; Lian et al., 2024; Liu et al., 2024; Rajoria et al., 2024; Song et al., 2025).

Tannery effluents are chemically different. Chromium is commonly introduced as Cr(III), but oxidative conditions, process chemicals, and mixed waste handling can produce or sustain Cr(VI) in certain streams. High organic loads, sulfide, chloride, alkalinity, suspended solids, and competing metal ions make these waters poor proxies for single-solute laboratory

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

solutions. Studies using real tannery wastewater repeatedly show that apparent sorption or reduction capacity obtained in deionized water is not directly transferable to industrial matrices.

2.2. Metallurgy, mining, chromite processing, cement, and refractory sources

Metallurgical and mineral-processing sources include stainless-steel operations, chromite ore processing residues, ferrochrome-related solids and leachates, ash, dust, and residues exposed to alkaline or oxidizing conditions. Of particular concern is chromium incorporated into Fe-bearing or spinel-like phases that can undergo weathering, reduction, or re-oxidation. The occurrence of Cr(VI) in such systems is therefore coupled to mineral transformation and residue aging rather than controlled only by aqueous dosing chemistry.

2.3. Wastewater descriptors that control treatment selection

For industrial design, a Cr(VI) concentration is insufficient by itself. At minimum, the feed should be characterized for total Cr, Cr(VI), pH, oxidation–reduction potential (ORP), ionic strength or conductivity, sulfate, chloride, nitrate, phosphate, carbonate/alkalinity, dissolved organic carbon, suspended solids, Fe, Al, Ca, Mg, Ni, Zn, Cu, and complexing agents. These variables determine whether reduction is kinetically accessible, whether Cr(III) will precipitate, whether sorption sites remain selective, and whether fouling, scaling, or competing current limits membranes or electrochemical systems.

Industrial-source heterogeneity is documented across effluent-characterization and treatment studies (Ameha et al., 2024; Arif et al., 2020; Dabai & Mohammed, 2024; Ke et al., 2025; Khan et al., 2022; Liu et al., 2020; Liu et al., 2024). Related published investigations include Ma et al. (2022), Rajoria et al. (2024), Song et al. (2025), Tao et al. (2022), Thiripelu et al. (2024), Tian et al. (2024), and Xiong et al. (2025). Related published investigations include (Yu & Liao, 2023; Yu & Yang, 2024).

The principal source-specific differences that should be resolved before technology selection are summarized in Table 1.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Table 1. Typical characteristics of Cr(VI)-containing industrial effluents and their treatment implications

Industrial source	Indicative Cr(VI) behavior	Typical pH tendency	Major coexisting species	Organic/solids burden	Main treatment challenge
Electroplating/surface finishing	Potentially high, segregated or mixed	Acidic to variable	Ni, Zn, Cu, Fe, sulfate, chloride, complexants	Low–moderate	Selective recovery vs. mixed-metal sludge
Tanning/leather	Often lower but matrix-complex	Variable, frequently alkaline in mixed streams	Cr(III), sulfide, chloride, sulfate, organics	High	Matrix competition, COD, sulfide, speciation control
Chromite processing/ferrochrome residues	Leachate controlled by mineral phases	Often alkaline	Fe, Al, Ca, Mg, sulfate, carbonate	Moderate–high solids	Long-term release and re-oxidation
Metallurgical / mining residues	Highly source dependent	Wide range	Fe, Mn, sulfate, silicate, other metals	High solids possible	Heterogeneity and residue stability
Pigments/chemical manufacture	Process-specific, sometimes concentrated	Acidic to alkaline	Salts, oxidants/reductants, organics	Variable	Interference with redox and separation
Cement / refractory / combustion	Usually leachate-driven	Neutral to alkaline	Ca, sulfate, carbonate, dissolved salts	High solids	Leaching control and solid stabilization

Note. Prepared by the author as a qualitative synthesis of the industrial sources and matrix effects discussed in the cited literature; values are intentionally described as source-dependent rather than universal concentration ranges.

Table 1 emphasizes that source segregation is a process variable, not just a wastewater-management practice. A relatively concentrated but compositionally simple rinse can be more amenable to chromium recovery than a lower-concentration mixed effluent containing complexants, surfactants, dissolved organics, and multiple metals. The critical design question is therefore not which technology has the highest published percentage removal, but which treatment train fits the specific chemical inventory and the intended fate of chromium.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

3. Chromium aqueous chemistry and Cr(VI) speciation

3.1. Oxidation states, acid–base equilibria, and redox coupling

In water-treatment practice, chromium chemistry is dominated by Cr(VI) oxyanions and hydrolyzed Cr(III) species. Under acidic conditions, $HCrO_4^-$ becomes important, while CrO_4^{2-} dominates as pH rises; dichromate becomes significant when total chromate concentration and acidity are sufficient. The negative charge of Cr(VI) species explains their affinity for protonated sorbents, anion exchangers, and positively charged membrane functionalities. In contrast, Cr(III) behaves primarily as a cation at low pH and progressively hydrolyzes as pH increases, eventually forming sparingly soluble hydroxide-rich phases.

Reductive treatment is strongly pH-dependent because proton participation makes many Cr(VI)-to-Cr(III) reactions faster and thermodynamically more favorable under acidic conditions. Yet the optimum pH for reduction is not necessarily the optimum pH for Cr(III) separation. Industrial treatment therefore usually requires staged pH control: an acidic reduction window followed by neutralization and precipitation, or a coupled sorption–reduction system designed to immobilize the produced Cr(III).

3.2. Matrix control of speciation and remobilization

ORP, dissolved oxygen, Fe(II)/Fe(III), Mn oxides, sulfides, organic matter, and mineral surfaces can shift chromium redox state and residence time. Ferrous iron and reduced sulfur species promote reduction, whereas Mn-bearing oxidants can re-oxidize Cr(III) under favorable conditions. This is especially important for long-term residue management: a sludge that passes a short-term leaching test immediately after treatment may not remain chemically equivalent during aging, drying, carbonation, or contact with oxidizing minerals.

Speciation quality assurance requires explicit control of transformations between collection and analysis. Researchers should report sample collection location and time, filtration status (filtered versus unfiltered, including nominal pore size), preservation chemistry, temperature, elapsed holding time, analytical method, detection/quantification limits, blanks, duplicate precision, matrix spikes, recovery, and interference checks. Fe(II), sulfides, organic reductants, oxidants, and particulate Mn can shift chromium oxidation states

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

during collection, filtration, preservation, transport, and storage. Dissolved Cr(VI), dissolved total Cr, and unfiltered total Cr should be reported as different analytical quantities. Follow method-specific storage requirements, and verify matrix stability rather than assume it; EPA Method 218.6 and its federal implementation guidance show why filtration/preservation and holding times depend on the method and matrix (U.S. Environmental Protection Agency, 1994; U.S. Environmental Protection Agency, n.d.-a). ORP indicates bulk redox conditions but cannot independently establish quantitative Cr(VI) conversion or total chromium removal.

The redox and mineral-surface interactions governing chromium remobilization have been investigated in complementary studies (Ambika et al., 2022; Anthony & Oladoja, 2022; Dai et al., 2024; Pakade et al., 2019; Rajapaksha et al., 2022; Rajput et al., 2021; Rodrigues et al., 2010). Related published investigations include (Stern et al., 2024; Xie et al., 2025; Yao et al., 2020; Yuan et al., 2023).

Figure 1 summarizes the distinct pH-sensitive roles of Cr(VI) oxyanions, reductive conversion, and Cr(III) separation. The diagram is deliberately qualitative because quantitative predominance boundaries depend on total concentrations, activity corrections, ligands, and solid phases.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

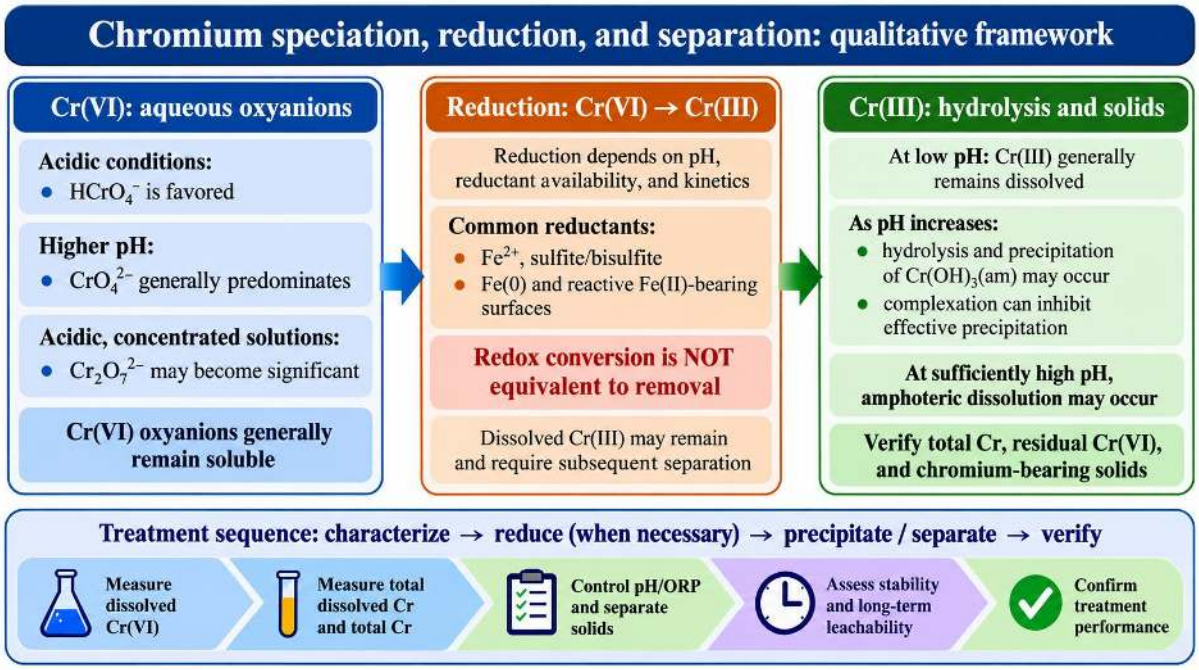


Figure 1. Conceptual relationship between pH, redox conditions, Cr(VI) oxyanions, and Cr(III) hydrolysis/precipitation.

Note. Original conceptual illustration developed for this review. Species boundaries are qualitative and depend on pH, total concentration, ionic strength, ligands, and redox conditions; the diagram is not a quantitative Pourbaix diagram.

Figure 1 shows the fundamental process-design tension: conditions that favor rapid Cr(VI) reduction can leave Cr(III) soluble, whereas conditions that favor Cr(III) precipitation may slow some reductive pathways or alter adsorbent surface charge. This coupling is a major reason why treatment should be evaluated as a sequence of chemical states and phase transfers rather than as a single removal percentage.

4. Toxicity, environmental fate, and regulatory framework

4.1. Why Cr(VI) and Cr(III) cannot be treated as equivalent risk metrics

Cr(VI) is generally more mobile and biologically hazardous than Cr(III) because chromate can exploit anion transport pathways, enter cells, and undergo intracellular reduction that generates reactive intermediates and oxidative stress. Cr(III), while not benign in all contexts, is less mobile under many circumneutral conditions and can be strongly sorbed or precipitated. Risk assessment therefore requires oxidation-state information whenever Cr(VI) occurrence is plausible.

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

4.2. Environmental transport, transformation, and regulatory interpretation

In soils, groundwater, surface water, and industrial residues, chromium fate reflects competing reduction, oxidation, sorption, dissolution, and precipitation pathways. Organic matter, Fe-bearing minerals, and sulfides can attenuate Cr(VI), whereas Mn oxides can regenerate Cr(VI) from Cr(III) under suitable conditions. Regulatory compliance based solely on total Cr helps control mass, but it may obscure speciation-dependent hazards; conversely, a Cr(VI)-specific limit without accounting for total Cr can underestimate chromium transferred to another aqueous or solid phase.

Toxicological, environmental, and regulatory research establishes the importance of speciation-resolved monitoring (Alvarez et al., 2021; Bashir et al., 2022; Bayuo, 2021; Cao et al., 2022; Chen & Tian, 2021; Du et al., 2023; Flint et al., 2021). Related published investigations include (Hessel et al., 2021; Islam et al., 2022; Josué et al., 2020; Lu et al., 2024; Meaza et al., 2024; Mishra & Bharagava, 2016; Pakhale & Gogate, 2024). Related published investigations include (Park et al., 2022; Punia et al., 2021; Qin et al., 2020; Ren et al., 2022; Sassi et al., 2021; Shi et al., 2023; Singh et al., 2022). Related published investigations include Sinha et al. (2022), Tan et al. (2023), Tang et al. (2021), Ukhurebor et al. (2021), Wang et al. (2024), Whitaker et al. (2018), and Zhang et al. (2022).

Regulatory values should be compared only after identifying the jurisdiction, regulated medium, chromium species, and legal object. In particular, drinking-water thresholds are not industrial-effluent discharge permits, and waste-classification criteria are not aqueous discharge criteria. Table 5 provides narrowly defined examples from official sources; regional requirements and license-specific conditions may be more restrictive.

Table 5. Examples of non-interchangeable regulatory chromium endpoints (official sources)

Jurisdiction/object	Chromium metric	Value	Official source	Interpretive limit
Brazil: industrial discharge	Cr(VI)	0.1 mg/L	CONAMA Resolution 430/2011	Effluent discharge; licensing and current amendments require verification
Brazil: industrial discharge	Cr(III)	1.0 mg/L	CONAMA Resolution 430/2011	Separate from Cr(VI); not a total-Cr drinking-water limit

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Jurisdiction/object	Chromium metric	Value	Official source	Interpretive limit
United States: federal drinking water	Total chromium	0.1 mg/L	U.S. EPA, SDWA	Drinking-water MCL; not a national industrial Cr(VI) discharge limit
WHO: drinking-water guidance	Total chromium	0.05 mg/L, provisional	WHO Guidelines for Drinking-water Quality	Guideline, not an industrial discharge standard

Note. Values are associated with different compliance objectives and are not directly ranked by numerical magnitude. Industrial site permits, state rules, receptor-water standards, waste classification, and occupational limits require separate legal assessment. A CONAMA regulatory revision was under discussion during 2026; applicability should be reconfirmed against the legally effective text immediately before submission. Sources: Conselho Nacional do Meio Ambiente (2011); U.S. Environmental Protection Agency (n.d.-b); World Health Organization (2026).

5. Conventional chemical treatment

5.1. Reduction–neutralization–precipitation as the industrial benchmark

The conventional benchmark involves chemically reducing Cr(VI), typically with ferrous salts or sulfur-based reductants, then adjusting pH, precipitating Cr(III) hydroxide, and performing coagulation/flocculation, clarification, and sludge dewatering. Its enduring advantage is not mechanistic novelty but operational familiarity, rapid kinetics, readily available reagents, and compatibility with conventional wastewater infrastructure. Its disadvantages are equally clear: chemical consumption, iron-rich sludge, sensitivity to pH control, and loss of chromium as a mixed residue rather than a recoverable product.

The following reaction illustrates representative acidic Fe(II) reduction stoichiometry; dichromate is not necessarily the dominant feed species because Cr(VI) speciation depends on pH and total concentration:

$$Cr_2O_7^{2-} + 6\ Fe^{2+} + 14\ H^+ \rightarrow 2\ Cr^{3+} + 6\ Fe^{3+} + 7\ H_2O$$

The stoichiometry demonstrates why acidic reduction and iron dosing are linked to downstream sludge production. Excess reductant can provide a kinetic safety margin, but it also increases dissolved iron, solids generation, and the burden on clarification and dewatering. After reduction, pH is raised to promote $Cr(OH)_3$ formation; simultaneous $Fe(OH)_3$ formation can improve scavenging but further increases sludge mass.

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

ORP may support reagent dosing and endpoint control only when calibrated to matrix-specific speciation measurements. A favorable ORP cannot establish a nondetectable Cr(VI) concentration, complete reductant/electron utilization, or total chromium removal.

5.2. Performance metrics beyond Cr(VI) disappearance

A credible evaluation should report at least influent and effluent Cr(VI), total dissolved Cr, total Cr, reagent dose, pH and ORP trajectory, sludge production, residual reductant, settling or filtration behavior, and leachability of the final solid. If only Cr(VI) is measured, quantitative reduction can be incorrectly described as removal. If only total Cr is measured, the redox mechanism and residual Cr(VI) risk remain uncertain.

For an appropriately defined control volume and steady-state sampling period, chromium inventory closure is $C_{Cr}\ (\%) = 100 \times [\Sigma_j M_{Cr,j,out} / M_{Cr,in}]$, where aqueous-stream chromium mass is $M_{Cr,j} = C_{Cr,j} \times V_j$, and solid-stream chromium mass is $M_{Cr,j} = m_j \times w_{Cr,j}$. Batch inventories must include initial and final liquid, precipitate, sorbent, recovered product, retained equipment deposits, wash liquor, regenerant, and other outputs as applicable. In flow operation, masses are integrated from flow rates and time-dependent concentrations. Report measurement uncertainty and any unallocated chromium; a universal closure tolerance is not justified independently of the measurement method and matrix.

A Cr(VI) concentration-based disappearance metric may be defined as $R_{Cr(VI)}\ (\%) = 100 \times [1 - C_{Cr(VI),out} / C_{Cr(VI),in}]$ for comparable inlet/outlet water volumes or flows. With unequal flows, use corresponding Cr(VI) mass loads. In contrast, total-chromium removal from treated water is $R_{Cr,total,water}\ (\%) = 100 \times [1 - M_{Cr,total,out,treated\ water} / M_{Cr,total,in,water}]$. Neither indicator alone establishes chromium recovery or complete system closure. If Cr(VI) is transferred to a concentrate without reduction, the first metric represents disappearance from the treated stream, not verified chemical reduction. A reduction yield should instead be demonstrated with species-resolved chromium inventories and validated chemical controls.

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Chemical-treatment studies reveal the operational trade-offs between reduction efficiency, dose, and sludge generation (Chen et al., 2024; Cong et al., 2022; Hojabri et al., 2024; Lan et al., 2024; Villabona-Ortíz et al., 2021).

Table 2 lists the minimum mass-balance metrics recommended for comparing reductive and separative processes.

Table 2. Minimum performance metrics required to distinguish Cr(VI) reduction from chromium removal

Metric	What it demonstrates	Why it matters
Influent/effluent Cr(VI)	Redox conversion or selective separation	Directly tracks the hazardous oxidation state
Dissolved total Cr	Chromium remaining in the aqueous phase	Detects dissolved Cr(III) after reduction
Total Cr including solids	Overall chromium inventory	Supports mass-balance closure
pH and ORP trajectory	Chemical conditions during treatment	Explains redox and precipitation windows
Solid-phase Cr and leachability	Transfer and stability of chromium	Distinguishes removal from unstable storage
Regenerant/concentrate Cr	Chromium transferred to secondary streams	Required for recovery and disposal accounting
Reagent/energy use	Process burden	Links removal performance to OPEX and environmental load

Note. Prepared by the author from the mass-balance logic used throughout this critical review.

Table 2 shifts the comparison from a single endpoint to a chromium inventory. This matters when processes combine reduction, sorption, precipitation, and membrane concentration because the same chromium atom can move between oxidation states and phases without leaving the treatment system.

6. Adsorption and ion-exchange processes

6.1. Carbonaceous, biopolymeric, mineral, and Fe-based sorbents

Researchers have widely investigated activated carbon, biochar, modified agricultural residues, chitosan, cellulose-derived materials, Fe/Mn oxides, magnetic composites, sludge-derived carbons, and functionalized polymers for Cr(VI). Their apparent capacity reflects a mixture of electrostatic attraction, ion exchange, surface complexation, pore accessibility,

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

and—in many carbonaceous or Fe-bearing systems—partial reduction to Cr(III). Mechanism attribution is therefore essential: a material described as an adsorbent may actually function as a coupled adsorbent–reductant.

Very high Langmuir capacities can help compare materials under standardized conditions, but they poorly predict industrial throughput when measured at low ionic strength, optimized pH, long contact time, and single-solute loading. For scale-up, fixed-bed breakthrough, hydraulic resistance, regeneration efficiency, cycle stability, attrition, and selectivity in the presence of sulfate, chloride, nitrate, phosphate, and competing metals are more informative than equilibrium capacity alone.

For fixed beds, distinguish fitted equilibrium capacity q_max from dynamic working capacity at a defined breakthrough limit. At minimum, report empty-bed contact time EBCT = V_bed/Q, treated bed volumes BV = V_treated/V_bed, normalized breakthrough C_out/C_in versus BV, operational loading at breakthrough and exhaustion, pressure drop, and bed attrition. Also quantify regeneration recovery, residual chromium in the regenerant, usable capacity retention over successive cycles, and final spent-media handling. Ion-exchange selectivity must be challenged using actual sulfate, chloride, nitrate, bicarbonate/carbonate, and phosphate mass loads, rather than arbitrarily chosen molar competition ratios.

6.2. Ion exchange and regeneration

Anion-exchange resins and positively charged polymeric materials can offer high selectivity for chromate species, particularly when streams are sufficiently clean to avoid severe fouling. Their main advantage is that they concentrate chromium into a regenerant suitable for recovery, rather than irreversibly embedding it in a large sludge mass. The trade-off is secondary brine generation and competition from abundant non-target anions. Practical performance therefore depends on selectivity coefficients, bed volumes treated, regeneration chemistry, and chromium recovery from the regenerant.

Adsorbent and ion-exchange studies highlight divergent mechanisms and the importance of regeneration and matrix competition (Ali et al., 2023; Alqarni et al., 2024; Bian & Shao, 2024; Dahiya et al., 2023; Deng et al., 2020; Du et al., 2024; Guo et al., 2020). Related

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

published investigations include (Gusu et al., 2023; He et al., 2024; Jobby et al., 2018; Khalil et al., 2020; Liu et al., 2021; Mao et al., 2022; Mortazavian et al., 2022). Related published investigations include (Sangkarak et al., 2020; Tejada-Tovar et al., 2020; Tian et al., 2024; Tie et al., 2023; Tie et al., 2024; Villabona-Ortíz et al., 2024). Related published investigations include (Yin et al., 2020).

7. Membrane and electrochemical technologies

7.1. Pressure-driven, osmotic, and facilitated membrane processes

Nanofiltration, reverse osmosis, forward osmosis, ultrafiltration coupled with charged functional layers, and supported or liquid membranes can separate Cr(VI) while producing a reusable permeate. Their defining feature is phase separation rather than chemical destruction: chromium remains in a concentrate, draw solution, carrier phase, or retained fraction that must be recovered or managed. Thus, excellent rejection is only the first half of the flowsheet.

Membrane evaluations should jointly report Cr(VI) and total-Cr rejection, water recovery, permeate flux, chromium enrichment/concentration factor, specific electrical/pressure energy, fouling and cleaning frequency, and chromium mass recovered or disposed of in the retentate. Concentrate quality is not equivalent to a marketable chromium product, and its disposition must be part of the process balance.

7.2. Electrocoagulation, electroreduction, electrodialysis, and hybrid systems

Electrochemical treatment can generate coagulant in situ, drive direct or indirect reduction, transport ions through selective membranes, or couple reduction with precipitation. These processes can reduce chemical handling and respond quickly to flow changes, but performance depends on current efficiency, conductivity, electrode material, passivation, mass transfer, pH gradients, and the energy required per mass of chromium removed. Flow-through studies are especially valuable because they expose hydraulic and electrode-aging limitations that batch beakers cannot represent.

Electrical demand should be normalized as E_S (kWh kg^{-1} Cr removed) = E_electrical (kWh)/m_Cr removed (kg), using measured system-level electricity including pumps and

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

auxiliary equipment when defined. For a constant-voltage/current test, idealized electrical input is U × I × t with consistent unit conversion. Report electrode consumption per kg Cr removed, current efficiency under the verified electrochemical pathway, competing hydrogen/oxygen reactions, passivation, hydraulic residence time, and pH-gradient effects. A high concentration-based removal percentage cannot substitute for a charge/electron balance.

Electrochemical and membrane investigations provide evidence on selective transport, reduction, and concentrate management (Alguacil & Robla, 2023; Fu et al., 2024; Kabdaşlı & Tünay, 2023; Lian et al., 2024; Mantel et al., 2022; Mondal & Saha, 2020; Stern et al., 2021). Related published investigations include (Stern et al., 2022; Wan et al., 2024; Zhang et al., 2021).

Figure 2 schematically compares the main fate pathways created by membrane and electrochemical treatments.

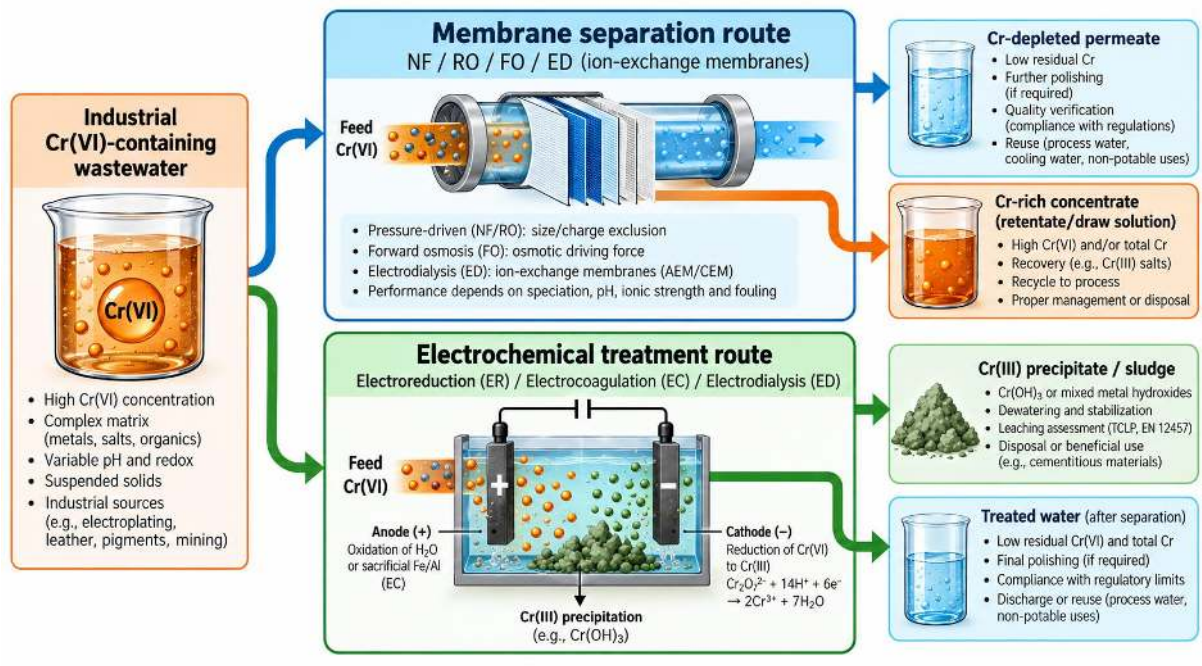


Figure 2. Conceptual contaminant-flow comparison for membrane and electrochemical Cr(VI) treatment routes.

Note. Developed by the author from the process pathways discussed in this review.

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Figure 2 makes explicit that membrane rejection transfers chromium to a concentrate, whereas electrochemical routes frequently transfer it to a solid phase. Neither route is intrinsically waste-free. The technology's downstream value depends on whether the concentrated chromium stream can be recovered, recycled, or immobilized with demonstrable long-term stability.

8. Emerging reduction and remediation technologies

8.1. Zero-valent iron, bimetallic systems, and reactive composites

For ZVI and related reactive media, report Fe dissolution, electron utilization where determinable, passivation, corrosion-solid burden, aqueous/solid chromium partitioning, and post-aging remobilization. Redox conversion without solid-phase stability remains an incomplete endpoint.

Zero-valent iron (ZVI), nanoscale ZVI, Fe-based composites, bimetallic particles, and carbon-supported reactive materials exploit electron transfer from Fe(0), Fe(II), or coupled metals to reduce Cr(VI). Their attraction lies in rapid reduction and simultaneous sorption or coprecipitation. Their limitations include passivation, agglomeration, non-productive corrosion, sensitivity to water chemistry, and uncertainty about the stability of Cr-bearing corrosion products. Researchers have therefore used surface modification, carbon shells, sulfur species, and mechanical activation to improve electron utilization and maintain reactive sites.

ZVI and reactive-iron studies should quantify Fe dissolution per mass Cr transformed, electron-utilization efficiency (where measurable), reactive-media loss, hydrogen evolution (if relevant), corrosion-solid generation, Cr distribution between water and Fe-bearing precipitates, passivation kinetics, and aging/leaching behavior. Fe-rich corrosion products should not automatically be designated stable sinks.

8.2. Photocatalytic and advanced reduction systems

Photocatalytic reports should control diphenylcarbazide-colorimetric interference from colored donors, turbidity, suspended catalysts, dissolved co-reactants, and nanoparticles, preferably with validated orthogonal Cr(VI) and total-Cr analyses. Photon use, sacrificial donor

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

demand, catalyst recovery, and the destination of aqueous Cr(III) after photoreduction determine process relevance.

Photocatalytic systems based on TiO_2, heterojunction semiconductors, carbon quantum dots, and related materials can reduce Cr(VI) using photogenerated electrons, often with sacrificial electron donors. The central scale-up questions are photon utilization, catalyst recovery, turbidity, competition for reactive species, catalyst lifetime, and whether the resulting Cr(III) is subsequently separated. Photocatalytic studies that report only spectrophotometric Cr(VI) disappearance without total-Cr or solid-phase analysis cannot establish complete chromium removal.

Reactive iron and photochemical studies indicate substantial mechanistic promise but heterogeneous process readiness (Bejarano-Meza et al., 2024; Brasili et al., 2020; Chen et al., 2024; Djellabi et al., 2022; He et al., 2023; Hu et al., 2010; Liapun et al., 2023). Related published investigations include Liu et al. (2022), Ma et al. (2020, 2024), Mungan et al. (2024), Shen et al. (2024), and Sun et al. (2022). Related published investigations include (Verma et al., 2022; Wan et al., 2024; Wang et al., 2021; Wu et al., 2021; Wu et al., 2026; Yang et al., 2022; Ye et al., 2021). Related published investigations include (Zhao et al., 2022; Zhou et al., 2020).

9. Biological and nature-based treatment

9.1. Microbial reduction, biosorption, and coupled metabolism

Biological-process studies should quantify electron-donor demand, toxicity thresholds, biomass production, contact time, stable conversion under variable loading, and the fate of immobilized Cr after biomass turnover.

Bacteria, fungi, algae, mixed microbial communities, and microbial fuel cells can reduce Cr(VI) enzymatically or indirectly through biologically generated reductants. Biomass can also sorb chromium, creating coupled biotransformation and biosorption. These systems are attractive where low-energy treatment and passive or semi-passive operation are priorities, but Cr(VI) toxicity can inhibit the very organisms needed for treatment, and electron-donor demand can become a major operating variable.

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

9.2. Permeable reactive barriers and biologically assisted systems

Permeable reactive barriers require long-duration hydraulic evidence, including residence-time distribution, channeling, clogging, reactive capacity exhaustion, and periodic Cr(VI), dissolved-total-Cr, and solid-phase measurements.

Constructed wetlands and permeable reactive barriers can combine microbial reduction, Fe/S chemistry, sorption, and precipitation over long residence times. Their strength is sustained in situ treatment; their weakness is less direct control over local geochemical changes, clogging, channeling, biomass decay, and re-oxidation. Systems combining sulfate-reducing bacteria with Fe-bearing reactive media illustrate the potential benefit of self-generating FeS-rich zones, but long-term performance must be verified under field-relevant hydraulic loading.

Biological and permeable-barrier studies link reduction capacity to biogeochemistry, permeability, and operating stability (Huang et al., 2020; Jiang et al., 2022; Liang et al., 2024; Liu et al., 2020; Mu et al., 2024; Ouyang et al., 2023; Ramli et al., 2023). Related published investigations include (Xu et al., 2024; Yang et al., 2021; Zhuang et al., 2023).

10. Effect of real wastewater composition on Cr(VI) treatment

10.1. pH, major anions, hardness, metals, organics, and suspended solids

The discrepancy between synthetic and real wastewater performance is not random; it follows predictable competition and transport mechanisms. Sulfate, chloride, nitrate, phosphate, and carbonate compete for charged sorption sites and ion-exchange capacity, modify electrical double layers, and change ionic strength. Ca and Mg can promote scaling, while Fe, Al, Ni, Zn, and Cu can compete for ligands, consume reagents, or coprecipitate with chromium. Dissolved organic matter can reduce Cr(VI) and foul surfaces, and suspended solids can shield reactive sites or add sorption capacity.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

10.2. Why batch removal percentages overstate industrial readiness

Single-solute batch tests often maximize contact efficiency: the material is fully dispersed, mixing is intense, pH is adjusted to the optimum, and the sorbent is exposed to a known chromium concentration without continuously replenished competitors. Real systems impose hydraulic residence time, breakthrough, head loss, electrode scaling, membrane fouling, solids loading, variable influent composition, and operational interruptions. For this reason, evidence from real wastewater and continuous flow should be treated as qualitatively more valuable than an incremental improvement in a batch removal percentage.

Studies using realistic aqueous matrices underscore the effect of competing ions and mixed contaminants (Cheng et al., 2021; Ezzahi et al., 2026).

The principal matrix effects that explain these discrepancies are summarized in Table 3.

Table 3. Factors responsible for discrepancies between Cr(VI) treatment in synthetic solutions and real industrial effluents

Matrix factor	Mechanistic effect	Likely consequence
pH/alkalinity	Controls speciation, surface charge, reduction, and Cr(III) precipitation	Shift in optimum dose and incomplete phase separation
Sulfate/chloride / nitrate	Compete for anion sites; alter ionic strength	Lower sorption/IX capacity and earlier breakthrough
Phosphate/carbonate	Strong competition and possible precipitation/scaling	Reduced selectivity, scaling, and surface blocking
Fe, Al, Ca, Mg	Coprecipitation, scaling, and reagent consumption	Higher solids production and membrane/electrode fouling
Ni, Zn, Cu	Competition and mixed-metal chemistry	Lower chromium selectivity and mixed residues
Dissolved organic matter	Complexation, redox activity, and fouling	Variable kinetics and regeneration difficulty
Suspended solids	Site shielding, filtration load, and heterogeneous sorption	Poor reproducibility and higher pretreatment demand
High ionic strength	Charge screening and activity effects	Different equilibrium and kinetics than in deionized water

Note. Prepared by the author based on the real-wastewater and competitive-ion evidence synthesized in this review.

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Table 3 explains why a technology may be scientifically valid yet industrially underperform. The correct response is not to reject laboratory screening, but to design a deliberate validation sequence in which matrix complexity, flow regime, and scale are increased while chromium speciation and mass balance remain measurable.

11. Process integration, chromium recovery, and circularity

11.1. Hybrid treatment trains

No single unit operation is likely to be optimal across the full range of Cr(VI) concentrations and matrices. High-strength segregated streams may justify recovery-oriented separation; medium-strength acidic streams may favor reduction followed by selective precipitation; dilute effluents may require adsorption, ion exchange, membrane polishing, or electrochemical treatment. Hybridization is therefore most useful when each unit operation is assigned a distinct function rather than when two high-performing laboratory technologies are simply combined.

11.2. Recovery, reuse, and residue management

Chromium recovery must be demonstrated by a process-level chromium yield and product specification, not inferred from a high concentration in retentate or regenerant. Reporting should include elemental chromium recovery, product purity, impurities/co-metals, downstream chemical demand, and a defined reuse or market destination. Residues require a designed durability program where relevant: oxic aging, Mn-oxide contact, wet–dry cycles, carbonation, pH shifts, leach tests after aging, and renewed Cr(VI) speciation. A fresh-sludge extraction result cannot establish long-term immobilization.

Circularity requires distinguishing chromium recovery from chromium immobilization. Recovery produces a chromium-rich stream or product that can re-enter an industrial process after purification; immobilization produces a residue intended for safe disposal or beneficial use. Electroplating sludge recycling, selective leaching, controlled precipitation, and concentrate management show that chromium can sometimes be returned to productive use, but purity requirements and economics depend strongly on co-metals and the destination process.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Integration and recovery investigations emphasize that residual solids and concentrate streams require explicit management (Bratovcic et al., 2022; Du et al., 2023; Sun et al., 2025; Wang et al., 2022; Wang et al., 2024; Wu et al., 2025).

An integrated treatment train that preserves chromium mass balance and explicitly identifies secondary streams is shown in Figure 3.

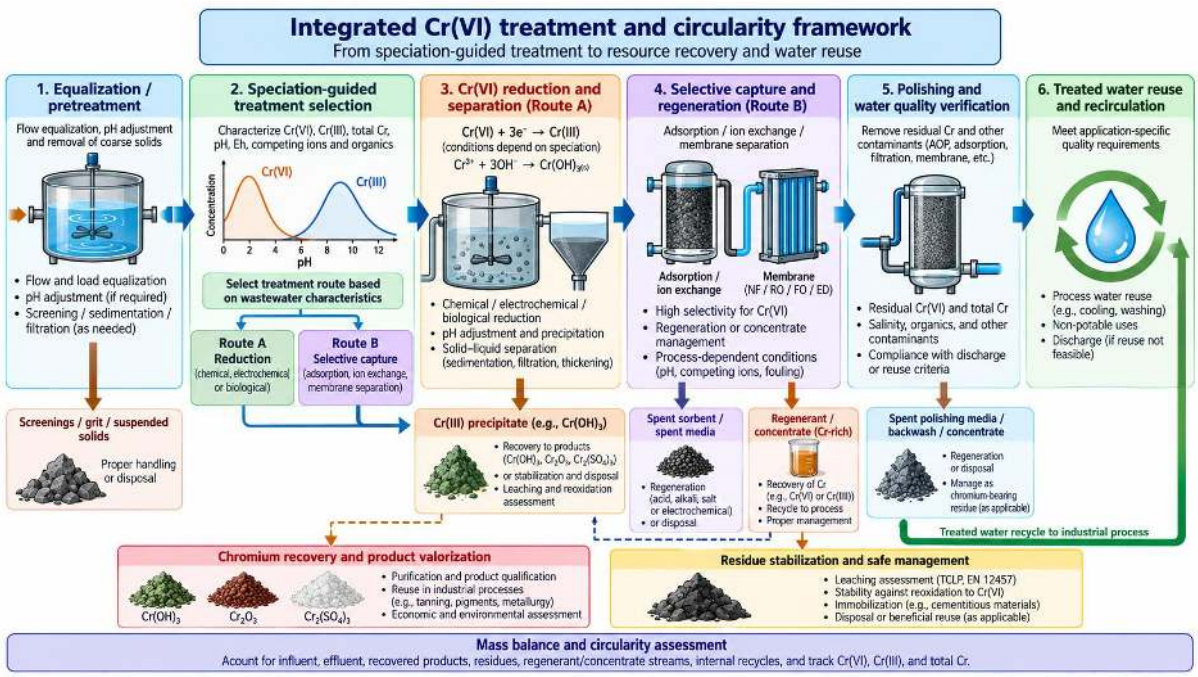


Figure 3. Integrated Cr(VI) treatment, chromium recovery, residue management, polishing, and water-reuse framework.

Note. Developed by the author as a process-integration synthesis based on the studies cited in Sections 5–11.

Figure 3 reframes "treatment" as a network of material destinations. The chromium-containing side streams—sludge, spent sorbent, regenerant, and membrane concentrate—are not peripheral wastes; they are central outputs that determine whether the process is genuinely circular, merely transfers contamination, or produces a stable final sink.

12. Techno-economic, environmental, and scale-up assessment

12.1. Reagent, energy, sludge, regeneration, CAPEX, and OPEX

Techno-economic and life-cycle comparisons must disclose the functional unit and system boundary. Appropriate but non-equivalent units include per m^3 influent treated, per kg

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Cr removed from water, per kg Cr(VI) detoxified, per kg chromium recovered to specification, and per m^3 reusable water produced. Consistent inventories should separately allocate reagents, electric energy, electrodes, membrane/sorbent replacement, sludge and concentrate mass, transport, final treatment, and reclaimed-water credits. TEA and LCA conclusions are not comparable when boundaries or functional units differ.

Industrial selection requires normalizing performance by resource intensity. Reduction–precipitation may have modest equipment complexity but substantial reagent and sludge costs. Membrane systems can lower solids generation but create pressure-driven energy demand and concentrates. Electrochemical processes exchange some chemical consumption for electricity and electrode replacement. Adsorbents may look inexpensive on a mass basis but become costly when you include low working capacity, frequent regeneration, or attrition. For emerging materials, synthesis complexity and precursor purity can dominate life-cycle and economic performance even when laboratory removal is excellent.

12.2. TRL and the laboratory-to-industrial evidence gap

Technology readiness should be assigned from the strongest demonstrated operating context, not from the sophistication of the material. A nanocomposite with 99.9% Cr(VI) removal in a 100 mL batch test remains low in translational evidence, whereas a conventional process with lower nominal removal but sustained full-scale operation may provide much stronger engineering confidence. Pilot-scale studies that report chemical consumption, cost, life-cycle impacts, hydraulic behavior, and real-wastewater performance are therefore disproportionately valuable.

Techno-economic and scale-up evidence underlines the need for consistent functional units and transparent operating boundaries (An et al., 2024; Bamane et al., 2021; Boustila et al., 2022; Costa et al., 2020; Hassan et al., 2024; Husain et al., 2025; Huynh et al., 2026). Related published investigations include (Singh et al., 2022; Tan et al., 2020).

Table 4 presents a comparative decision matrix. The ratings are qualitative and intentionally emphasize evidence quality and residual-stream management rather than only peak removal.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Table 4. Comparative assessment of principal Cr(VI) treatment technology families

Technology family	Cr(VI) conversion/removal	Total-Cr control	Secondary residue	Regeneration/recovery	Real-effluent evidence	Translational maturity tendency
Reduction–precipitation	High	High when precipitation/solid separation is controlled	High sludge	Low–moderate recovery unless selectively designed	Strong	High
Adsorption/biochar	High in optimized tests	Variable; mechanism-dependent	Spent sorbent / regenerant	Moderate if regenerable	Moderate	Low–moderate
Ion exchange	High	High via phase transfer	Regenerant brine	High recovery potential	Moderate	Moderate–high
Membranes	High rejection	High in permeate; Cr retained in concentrate	Concentrate	Potentially high	Moderate	Moderate–high
Electrochemical	High	High when reduction and separation are coupled	Sludge/electrode residues	Moderate	Increasing	Moderate–high
ZVI / reactive media	High reduction	Variable immobilization	Reactive solids	Usually low	Moderate for barriers	Moderate
Photocatalysis	High Cr(VI) conversion in clear waters	Often uncertain unless Cr(III) separated	Catalyst + dissolved Cr(III)	Low–moderate	Limited	Low–moderate
Biological / nature-based	Moderate–high under compatible conditions	Variable; often coupled to solids	Biomass/sediments	Low–moderate	Moderate in remediation	Moderate

Note. Qualitative synthesis prepared by the author from the literature cited throughout the review. Ratings are context-dependent and should not be interpreted as universal technology rankings.

Table 4 indicates that the industrial benchmark remains difficult to displace when robustness, operator familiarity, and full-scale evidence are weighted heavily. Emerging

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

technologies become competitive when they address a specific weakness of the benchmark—such as chromium recovery, low-sludge polishing, selective treatment of dilute streams, or passive remediation—rather than merely achieving a higher batch removal percentage.

12.3. Cr(VI) Treatment Evidence Ladder

The following ladder is explicitly author-developed and unvalidated. It ranks the strength of translational evidence for this review, not formal TRL certification, numerical readiness assignment, or a validated study-quality score. Formal TRL should be reported only when an independently justified 1–9 mapping and demonstration context are provided.

To make evidence strength explicit, this review proposes a six-level hierarchy from single-solute batch tests to full-scale industrial operation. Advancement between levels should require not only a larger apparatus but also retention of analytical rigor: Cr(VI) and total Cr, mass balance, matrix composition, residual streams, stability, and operating cost should remain measurable as complexity increases.

Figure 4 presents the proposed ladder.

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

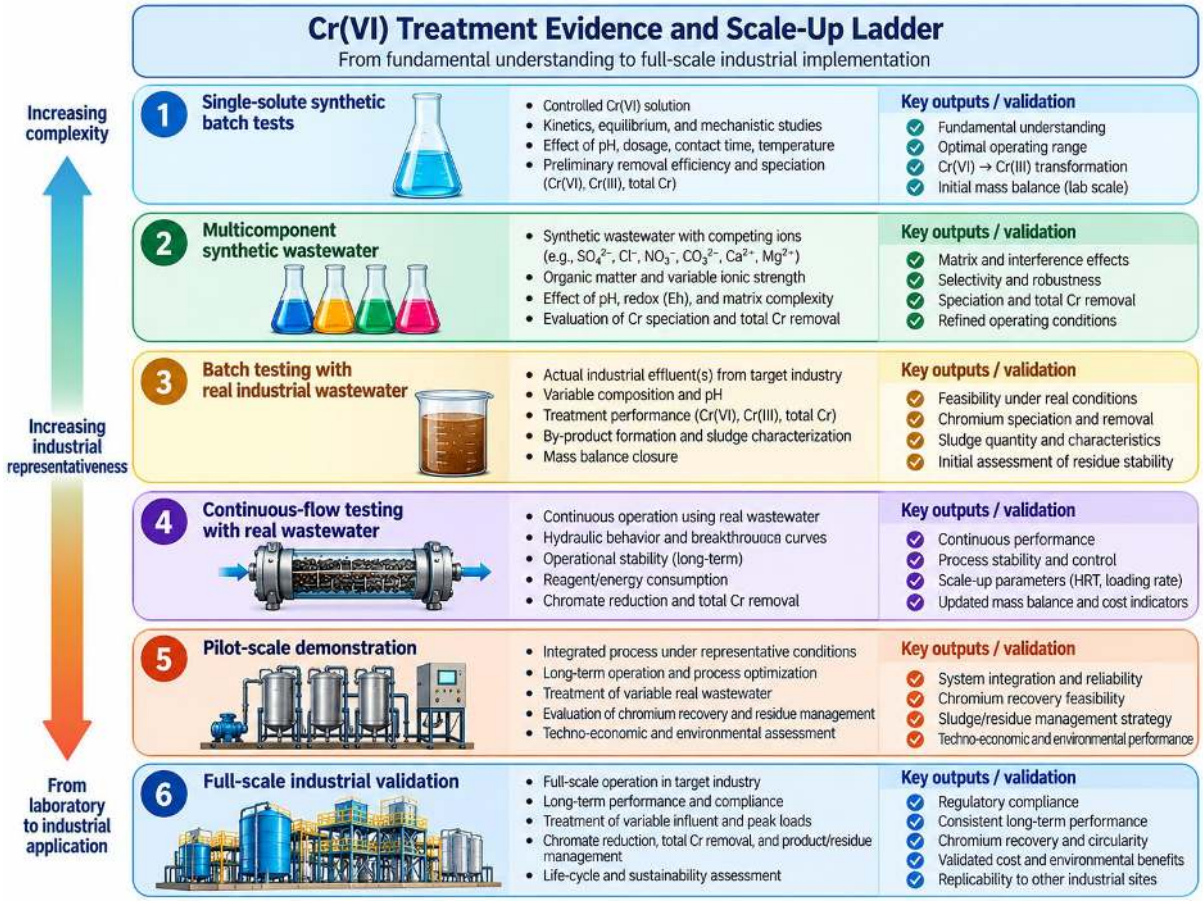


Figure 4. Cr(VI) Treatment Evidence Ladder for grading the translational strength of reported treatment performance.

Note. Developed by the author as the central evidence framework of this critical review.

Figure 4 provides a direct way to prevent overinterpretation. A Level 1 material can be mechanistically important, but it should not be described as industrially superior to a Level 5 or Level 6 process without comparable evidence. The ladder can also guide research design: each new study should state which level it addresses and which additional measurements are required for progression to the next level.

13. Critical knowledge gaps, future research directions, and conclusions

13.1. Critical knowledge gaps

The literature remains dominated by synthetic batch studies, often at initial Cr(VI) concentrations, pH values, and solid-to-liquid ratios chosen to maximize apparent performance rather than represent industrial conditions. Total chromium is frequently omitted after reductive

JIRRS
Journal International Review of Research Studies
Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

treatment, making it impossible to distinguish detoxification from complete removal. Speciation measurements are often limited to Cr(VI) colorimetry, and solid-phase chromium is insufficiently characterized. Regeneration data commonly cover only a few cycles, and breakthrough behavior, hydraulic stability, continuous-flow performance, and long-term residue leachability remain underreported.

A second gap is process comparability. Studies use different initial concentrations, dose definitions, contact times, pH-control methods, and reporting bases, yet are routinely ranked by percentage removal or Langmuir capacity. More rigorous reporting should include mass-based treatment capacity at realistic loading, chemical consumption per unit of Cr removed, energy intensity, water recovery, solid or concentrate generation, and uncertainty. Pilot and industrial datasets should be valued even when they show lower nominal efficiency because they reveal failure modes that idealized tests suppress.

13.2. Future research directions

Future work should prioritize speciation-resolved treatment, realistic multicomponent effluents, continuous-flow experimentation, chromium recovery, low-sludge flowsheets, regenerable sorbents and ion exchangers, selective electrochemical separation, hybrid reduction–separation systems, real-time Cr(VI)/ORP monitoring, and integrated techno-economic, life-cycle, and technology-readiness assessment. Standardized reporting templates would substantially improve cross-study comparability. Particular attention is needed for aging and re-oxidation of Cr-bearing residues, because short-duration extraction tests cannot represent long-term field geochemistry.

13.3. Conclusions

Evaluate Cr(VI) treatment as a coupled problem of speciation, redox transformation, phase separation, recovery, residue stability, and process scale. The most important conceptual correction is to stop treating Cr(VI) disappearance as equivalent to chromium removal. Reduction is often necessary for detoxification, but the resulting Cr(III) must still be separated, recovered, or immobilized in a demonstrably stable form. Likewise, membrane rejection and

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

adsorption can remove chromium from treated water while transferring it to concentrates or spent solids that remain part of the chromium inventory.

Conventional reduction–neutralization–precipitation remains the principal industrial benchmark because of robustness and maturity, but its sludge burden creates a clear incentive for selective recovery, hybrid flowsheets, and low-residue polishing technologies. Adsorption, ion exchange, membranes, electrochemical systems, ZVI, photocatalysis, and biological processes are most compelling when matched to an appropriate concentration range, matrix, and downstream chromium destination. Their industrial relevance depends more on real-world wastewater, continuous flow, regeneration, pilot-scale, and cost evidence than on peak laboratory removal.

The proposed Cr(VI) Treatment Evidence Ladder provides a practical framework for comparing studies without conflating mechanistic promise with industrial readiness. A defensible future treatment strategy should therefore optimize the combined objective of speciation control + total-chromium removal + chromium recovery + residue stability + cost + scale, rather than maximize a single Cr(VI) removal percentage.

Declarations

Funding. This review received no specific external funding.

Conflict of Interest. The author declares no conflict of interest.

Data Availability. No new experimental datasets were generated. All quantitative and qualitative evidence discussed in the review is traceable to the cited literature.

Author Contributions. The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

References

Alguacil, F. J., & Robla, J. I. (2023). Transport of chromium(VI) across a supported liquid membrane containing Cyanex 921 or Cyanex 923. Membranes, 13(2), 177. https://doi.org/10.3390/membranes13020177

Ali, A., Alharthi, S., Al-Shaalan, N. H., Naz, A., & Fan, H.-J. S. (2023). Efficient removal of hexavalent chromium (Cr(VI)) from wastewater using amide-modified biochar. Molecules, 28(13), 5146. https://doi.org/10.3390/molecules28135146

Alqarni, L. S., Algethami, J. S., El Kaim Billah, R., Alorabi, A. Q., Alnaam, Y. A., Algethami, F. K., Bahsis, L., Jawad, A. H., Wasilewska, M., & López-Maldonado, E. A. (2024). A

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

novel chitosan-alginate@Fe/Mn mixed oxide nanocomposite for highly efficient removal of Cr(VI) from wastewater: Experiment and adsorption mechanism. International Journal of Biological Macromolecules, 263, 129989. https://doi.org/10.1016/j.ijbiomac.2024.129989

Alvarez, C. C., Gómez, M. E. B., & Zavala, A. H. (2021). Hexavalent chromium: Regulation and health effects. Journal of Trace Elements in Medicine and Biology, 65, 126729. https://doi.org/10.1016/j.jtemb.2021.126729

Ambika, S., Kumar, M., Pisharody, L., Malhotra, M., Kumar, G., Sreedharan, V., Singh, L., Nidheesh, P. V., & Bhatnagar, A. (2022). Modified biochar as a green adsorbent for removal of hexavalent chromium from aqueous solution. Chemical Engineering Journal, 439, 135716. https://doi.org/10.1016/j.cej.2022.135716

Ameha, B., Nadew, T. T., Tedla, T. S., Getye, B., Mengie, D. A., & Ayalneh, S. (2024). The use of banana peel as a low-cost adsorption material for removing hexavalent chromium from tannery wastewater: Optimization, kinetic and isotherm study, and regeneration aspects. RSC Advances, 14(6), 3675–3690. https://doi.org/10.1039/D3RA07476E

An, S., Wang, Y., Qiao, H., Xiu, H., Liu, D., & Kuang, Y. (2024). Photoelectrocatalytic reduction of Cr(VI) in wastewater with a CuBi2O4 thin film photocathode. Catalysts, 14(5), 289. https://doi.org/10.3390/catal14050289

Anthony, E. T., & Oladoja, N. A. (2022). Process enhancing strategies for the reduction of Cr(VI) to Cr(III) via photocatalytic pathway. Environmental Science and Pollution Research, 29(6), 8026–8053. https://doi.org/10.1007/s11356-021-17614-z

Arif, Z., Sethy, N. K., Mishra, P. K., & Verma, B. (2020). Development of eco-friendly, self-cleaning, antibacterial membrane for the elimination of chromium(VI) from tannery wastewater. International Journal of Environmental Science and Technology, 17(10), 4265–4280. https://doi.org/10.1007/s13762-020-02753-6

Bamane, S. D., Bhojwani, V., Balkunde, P. L., Bhattacharya, M., Gupta, I., Mohapatra, A. K., Shekhar, A., & Singh, A. (2021). Smartphone-enabled field monitoring tool for rapid hexavalent chromium detection in water. Analytical and Bioanalytical Chemistry, 413(13), 3455–3469. https://doi.org/10.1007/s00216-021-03291-x

Bashir, M. S., Ramzan, N., Najam, T., Abbas, G., Gu, X., Arif, M., Qasim, M., Bashir, H., Shah, S. S. A., & Sillanpää, M. (2022). Metallic nanoparticles for catalytic reduction of toxic hexavalent chromium from aqueous medium: A state-of-the-art review. Science

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

of the Total Environment, 829, 154475. https://doi.org/10.1016/j.scitotenv.2022.154475

Bayuo, J. (2021). An extensive review on chromium(VI) removal using natural and agricultural waste materials as alternative biosorbents. Journal of Environmental Health Science and Engineering, 19(1), 1193–1207. https://doi.org/10.1007/s40201-021-00641-w

Bejarano-Meza, M., Deza-Carrasco, F. E., Salinas-Herrera, S., Flores-Calla, S., & Jimenez-Pacheco, H. G. (2024). Evaluation of Cr(VI) removal from tanning effluents using magnetic nanoparticles of Fe3O4 synthesized with Olea europaea bone extract. Molecules, 29(2), 534. https://doi.org/10.3390/molecules29020534

Bian, P., & Shao, Q. (2024). Efficient adsorption of hexavalent chromium in water by torrefaction biochar from lignin-rich kiwifruit branches: Experiment, 2D-COS and DFT. International Journal of Biological Macromolecules, 266, 131324. https://doi.org/10.1016/j.ijbiomac.2024.131324

Boustila, H., Boutillara, Y., Velasco, L. F., Djellali, A., & Tazibet, S. (2022). Tailoring activated carbon properties for Pb(II) and Cr(VI) removal from water in continuous mode. Chemical Engineering & Technology, 45(2), 258–265. https://doi.org/10.1002/ceat.202100331

Brasili, E., Bavasso, I., Petruccelli, V., Vilardi, G., Valletta, A., Dal Bosco, C., Gentili, A., Pasqua, G., & Di Palma, L. (2020). Remediation of hexavalent chromium contaminated water through zero-valent iron nanoparticles and effects on tomato plant growth performance. Scientific Reports, 10, 1920. https://doi.org/10.1038/s41598-020-58639-7

Bratovcic, A., Buksek, H., Helix-Nielsen, C., & Petrinic, I. (2022). Concentrating hexavalent chromium electroplating wastewater for recovery and reuse by forward osmosis using underground brine as draw solution. Chemical Engineering Journal, 431, 133918. https://doi.org/10.1016/j.cej.2021.133918

Cao, R., Liu, S., Yang, X., Wang, C., Wang, Y., Wang, W., & Pi, Y. (2022). Enhanced remediation of Cr(VI)-contaminated groundwater by coupling electrokinetics with ZVI/Fe3O4/AC-based permeable reactive barrier. Journal of Environmental Sciences, 112, 280–290. https://doi.org/10.1016/j.jes.2021.05.002

Chen, J., & Tian, Y. (2021). Hexavalent chromium reducing bacteria: Mechanism of reduction and characteristics. Environmental Science and Pollution Research, 28(17), 20981–20997. https://doi.org/10.1007/s11356-021-13325-7

Chen, N., Cui, X., Sun, X., Yang, X., Yang, W., Ren, N., Feng, Y., Tian, Y., & He, W. (2024). Advanced Cr(VI) removal from wastewater using migrating electric field-assisted

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

electrocoagulation combined with capacitive deionization technology. Journal of Water Process Engineering, 63, 105445. https://doi.org/10.1016/j.jwpe.2024.105445

Chen, W., Li, B., Yin, W., Zeng, W., Li, P., & Wu, J. (2024). Promoted iron corrosion and subsequent hexavalent chromium removal in zero-valent iron systems by oxidant activation. Chemosphere, 352, 141391. https://doi.org/10.1016/j.chemosphere.2024.141391

Cheng, H., Liu, Y., Li, X., He, H., & Kang, X. (2021). Efficient recovery of Cr(VI) from electroplating wastewater by iron-modified sludge-based hollow-structured porous carbon: Coexistence effects and competition for adsorption. RSC Advances, 11, 37233–37245. https://doi.org/10.1039/D1RA06969A

Cong, Y., Shen, L., Wang, B., Cao, J., Pan, Z., Wang, Z., Wang, K., Li, Q., & Li, X. (2022). Efficient removal of Cr(VI) at alkaline pHs by sulfite/iodide/UV: Mechanism and modeling. Water Research, 222, 118919. https://doi.org/10.1016/j.watres.2022.118919

Costa, A. W. M. C., Guerhardt, F., Ribeiro Júnior, S. E. R., Cânovas, G., Vanale, R. M., Coelho, D. F., Ehrhardt, D. D., Rosa, J. M., Tambourgi, E. B., Santana, J. C. C., & Souza, R. R. (2020). Biosorption of Cr(VI) using coconut fibers from agro-industrial waste magnetized using magnetite nanoparticles. Environmental Technology, 43(3), 465–477. https://doi.org/10.1080/09593330.2020.1752812

Dabai, A. I., & Mohammed, K. (2024). Biosorption and desorption of chromium using hybrid microalgae-activated sludge treatment system. Applied Water Science, 14, 16. https://doi.org/10.1007/s13201-023-02068-0

Dahiya, A., Bhardwaj, A., Rani, A., Arora, M., & Babu, J. N. (2023). Reduced and oxidized rice straw biochar for hexavalent chromium adsorption: Revisiting the mechanism of adsorption. Heliyon, 9(11), e21735. https://doi.org/10.1016/j.heliyon.2023.e21735

Dai, X., Luo, Y., Deng, J., Wen, J., He, Y., Yuan, Y., & Wang, Y. (2024). Ultra-efficient removal of aqueous hexavalent chromium by activated biochar nanoparticles derived from squid ink. Environmental Research, 263, 120185. https://doi.org/10.1016/j.envres.2024.120185

Deng, J., Li, X., Wei, X., Liu, Y., Liang, J., Shao, Y., Huang, W., & Cheng, X. (2020). Different adsorption behaviors and mechanisms of a novel amino-functionalized hydrothermal biochar for hexavalent chromium and pentavalent antimony. Bioresource Technology, 310, 123438. https://doi.org/10.1016/j.biortech.2020.123438

Djellabi, R., Su, P., Elimian, E. A., Poliukhova, V., Nouacer, S., Abdelhafeez, I. A., Abderrahim, N., Aboagye, D., Andhalkar, V. V., Nabgan, W., Rtimi, S., & Contreras, S. (2022). Advances in photocatalytic reduction of hexavalent chromium: From

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

fundamental concepts to materials design and technology challenges. Journal of Water Process Engineering, 50, 103301. https://doi.org/10.1016/j.jwpe.2022.103301

Du, Y., Ye, X., Hui, Z., Jiao, D., Xie, Y., Chen, S., & Ding, J. (2024). Synergistic effect of adsorption-photocatalytic reduction of Cr(VI) in wastewater with biochar/TiO2 composite. Physical Chemistry Chemical Physics, 26, 15891–15901. https://doi.org/10.1039/D4CP01226G

Du, Z., Yang, M., Yang, Y., Zhang, X., Chen, H., Ngo, H. H., & Liu, Q. (2023). Sulfur-modified biochar efficiently removes Cr(VI) from water by sorption and reduction. Environmental Engineering Science, 40(10), 427–438. https://doi.org/10.1089/ees.2023.0046

Du, J., Zeng, L., Zhang, S., Xiao, C., Zhang, G., Cao, Z., Li, Q., Wang, M., Guan, W., & Wu, S. (2023). Complete recycling of valuable metals from electroplating sludge: Green and selective recovery of chromium. Chemical Engineering Journal, 468, 143484. https://doi.org/10.1016/j.cej.2023.143484

Ezzahi, K., Rabichi, I., El Fels, L., Idouhli, R., & Rochdi, N. (2026). Valorization of olive stone waste-derived biochar for the continuous fixed-bed removal of Cr(VI), Pb(II), and Cd(II) from wastewater. Waste Management, 216, 115452. https://doi.org/10.1016/j.wasman.2026.115452

Flint, L. C., Arias-Paić, M. S., & Korak, J. A. (2021). Removal of hexavalent chromium by anion exchange: Non-target anion behavior and practical implications. Environmental Science: Water Research & Technology, 7, 2397–2413. https://doi.org/10.1039/D1EW00382H

Fu, S., Chen, Y., Wu, X., Ye, L., Xu, L., & Zhao, X. (2024). Biopolymer based composite nanofiltration membranes resistant to strong acids, alkalis and chlorine for Cr(VI) removal. Journal of Water Process Engineering, 67, 106284. https://doi.org/10.1016/j.jwpe.2024.106284

Guo, X., Liu, A., Lu, J., Niu, X., Jiang, M., Ma, Y., Liu, X., & Li, M. (2020). Adsorption mechanism of hexavalent chromium on biochar. ACS Omega, 5(42), 27323–27331. https://doi.org/10.1021/acsomega.0c03652

Gusu, G. L., Chebude, Y., & Alemayehu, E. (2023). Adsorptive removal of Cr(VI) from wastewater using magnetite–diatomite nanocomposite. AQUA—Water Infrastructure, Ecosystems and Society, 72(12), 2239–2261. https://doi.org/10.2166/aqua.2023.132

Hassan, N. S., Jalil, A. A., Bahari, M. B., Izzuddin, N. M., Fauzi, N. A. F. M., Jusoh, N. W. C., Kamaroddin, M. F. A., Saravanan, R., & Tehubijuluw, H. (2024). A critical review of MXene-based composites in the adsorptive and photocatalysis of hexavalent chromium

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

removal from industrial wastewater. Environmental Research, 259, 119584. https://doi.org/10.1016/j.envres.2024.119584

He, C., Ding, Y., Li, C., Yan, W., Mao, A., Wei, S., & Li, M. (2023). Cost-effective core@shell structured zero-valent iron nanoparticles@magnetic Fe3O4 for Cr(VI) removal. RSC Advances, 13, 26983–26994. https://doi.org/10.1039/D3RA03133K

He, C., Liu, Y., Qi, M., Liu, Z., Fujita, T., Wang, G., Ma, S., & Yang, W. (2024). A functionalized activated carbon adsorbent prepared from waste amidoxime resin for Cr(VI) removal. International Journal of Minerals, Metallurgy and Materials, 31, 585–598. https://doi.org/10.1007/s12613-023-2737-z

Hessel, E. V. S., Staal, Y. C. M., Piersma, A. H., den Braver-Sewradj, S. P., & Ezendam, J. (2021). Occupational exposure to hexavalent chromium. Part I. Hazard assessment of non-cancer health effects. Regulatory Toxicology and Pharmacology, 126, 105048. https://doi.org/10.1016/j.yrtph.2021.105048

Hojabri, S., Rajic, L., Zhao, Y., & Alshawabkeh, A. N. (2024). Simulation of hexavalent chromium removal by electrocoagulation using iron anode in flow-through reactor. Journal of Hazardous Materials, 476, 135195. https://doi.org/10.1016/j.jhazmat.2024.135195

Hu, C.-Y., Lo, S.-L., Liou, Y.-H., Hsu, Y.-W., Shih, K., & Lin, C.-J. (2010). Hexavalent chromium removal from near natural water by copper-iron bimetallic particles. Water Research, 44(10), 3101–3108. https://doi.org/10.1016/j.watres.2010.02.037

Huang, S.-W., Chen, X., Wang, D.-D., Jia, H.-L., & Wu, L. (2020). Bio-reduction and synchronous removal of hexavalent chromium from aqueous solutions using novel microbial cell/algal-derived biochar particles: Turning an environmental problem into an opportunity. Bioresource Technology, 309, 123304. https://doi.org/10.1016/j.biortech.2020.123304

Husain, A., Ayub, S., Khan, A. H., Alam, S. S., & Hasan, M. A. (2025). Pilot scale recovery, and removal of chromium from tannery wastewater by chemical precipitation: Life cycle assessment and cost analysis. Journal of Environmental Management, 391, 126502. https://doi.org/10.1016/j.jenvman.2025.126502

Huynh, T. N., Nguyen, D. T., Pham, H. H. P. U., Trinh, A. D., & Tran, Q. H. (2026). Highly efficient Cr(VI) removal from water using deep eutectic solvents: A sustainable and comprehensive approach. RSC Advances, 16(3), 2767–2782. https://doi.org/10.1039/D5RA08693K

Islam, S., Kamila, S., & Chattopadhyay, A. (2022). Toxic and carcinogenic effects of hexavalent chromium in mammalian cells in vivo and in vitro: A recent update. Journal

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

of Environmental Science and Health, Part C, 40(3–4), 282–315. https://doi.org/10.1080/26896583.2022.2158675

Jiang, Y., Yang, F., Dai, M., Ali, I., Shen, X., Hou, X., Alhewairini, S. S., Peng, C., & Naz, I. (2022). Application of microbial immobilization technology for remediation of Cr(VI) contamination: A review. Chemosphere, 286, 131721. https://doi.org/10.1016/j.chemosphere.2021.131721

Jobby, R., Jha, P., Yadav, A. K., & Desai, N. (2018). Biosorption and biotransformation of hexavalent chromium [Cr(VI)]: A comprehensive review. Chemosphere, 207, 255–266. https://doi.org/10.1016/j.chemosphere.2018.05.050

Josué, T. G., Almeida, L. N. B., Lopes, M. F., Santos, O. A. A., & Lenzi, G. G. (2020). Cr(VI) reduction by photocatalytic process: Nb2O5 an alternative catalyst. Journal of Environmental Management, 268, 110711. https://doi.org/10.1016/j.jenvman.2020.110711

Kabdaşlı, I., & Tünay, O. (2023). Hexavalent chromium removal from water and wastewaters by electrochemical processes: Review. Molecules, 28(5), 2411. https://doi.org/10.3390/molecules28052411

Ke, Y., Liang, S., Duan, H., Quan, J., Li, X., Hou, H., Hu, J., Yang, Y., Liu, X., Zuo, Y., & Yang, J. (2025). Insights into solidification mechanism of Cr(III) and Cr(VI) in chromite ore processing residue via composite geopolymers synthesized from calcined red mud and granulated blast furnace slag. Journal of Hazardous Materials, 496, 139185. https://doi.org/10.1016/j.jhazmat.2025.139185

Khalil, U., Shakoor, M. B., Ali, S., Rizwan, M., Alyemeni, M. N., & Wijaya, L. (2020). Adsorption-reduction performance of tea waste and rice husk biochars for Cr(VI) elimination from wastewater. Journal of Saudi Chemical Society, 24(11), 799–810. https://doi.org/10.1016/j.jscs.2020.07.001

Khan, A. A., Mukherjee, S., Mondal, M., Boddu, S., Subbaiah, T., & Halder, G. (2022). Assessment of algal biomass towards removal of Cr(VI) from tannery effluent: A sustainable approach. Environmental Science and Pollution Research, 29, 61856–61869. https://doi.org/10.1007/s11356-021-16102-8

Lan, Y., Sun, Y., Chu, S., Yang, B., Zhang, L., Xiao, L., Li, J., Yuan, X., Yan, X., Galvita, V. V., & Su, X. (2024). Efficient removal and transformation of Cr(VI) from alkaline wastewater to form a ferrochromium spinel multiphase via modified ferrite process. Chemosphere, 351, 141185. https://doi.org/10.1016/j.chemosphere.2024.141185

Lian, R., Liu, Y., Pan, Y., Ding, J., Wu, X., Lv, M., Wu, X., Chen, R., Ding, R., Liu, J., & Van der Bruggen, B. (2024). Recovering chromium from electroplating sludge using an

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

integrated technology of bipolar membrane electrodialysis and H2O2 oxidation. Chemosphere, 366, 143450. https://doi.org/10.1016/j.chemosphere.2024.143450

Liang, J., Li, X., Zheng, Y., Pang, Y., Zhao, Y., Wang, Y., Zhang, J., & Zhang, J. (2024). A novel advanced reduction process for the reduction of Cr(VI): Assistance of microbial metabolites. Journal of Hazardous Materials, 480, 136121. https://doi.org/10.1016/j.jhazmat.2024.136121

Liapun, V., Hanif, M. B., Sihor, M., Vislocka, X., Pandiaraj, S., Unnikrishnan, V. K., Thirunavukkarasu, G. K., Edelmannová, M. F., Reli, M., Monfort, O., Kočí, K., & Motola, M. (2023). Versatile application of BiVO4/TiO2 S-scheme photocatalyst: Photocatalytic CO2 and Cr(VI) reduction. Chemosphere, 337, 139397. https://doi.org/10.1016/j.chemosphere.2023.139397

Liu, L., Liu, G., Zhou, J., & Jin, R. (2021). Interaction between hexavalent chromium and biologically formed iron mineral-biochar composites: Kinetics, products and mechanisms. Journal of Hazardous Materials, 405, 124246. https://doi.org/10.1016/j.jhazmat.2020.124246

Liu, W., Chen, P., Chen, L., & Zhang, D. (2024). Selective extraction of chromium from chromium-bearing electroplating sludge by pressure oxidation alkaline leaching. Process Safety and Environmental Protection, 191, 65–74. https://doi.org/10.1016/j.psep.2024.08.096

Liu, Y., Yuan, J., Ning, Y., Tang, Y., Luo, S., & Jiang, B. (2020). Efficient reduction of Cr(VI) and immobilization of Cr driven by an iron-air fuel cell: Reaction mechanisms and electricity generation. Chemosphere, 253, 126730. https://doi.org/10.1016/j.chemosphere.2020.126730

Liu, Z., Yu, Y., Zhu, X., Fang, J., Xu, W., Hu, X., Li, R., Yao, L., Qin, J., & Fang, Z. (2022). Semiconductor heterojunctions for photocatalytic hydrogen production and Cr(VI) reduction: A review. Materials Research Bulletin, 147, 111636. https://doi.org/10.1016/j.materresbull.2021.111636

Liu, Z., Zheng, J., Liu, W., Liu, X., Chen, Y., Ren, X., Ning, P., & Lin, Z. (2020). Identification of the key host phases of Cr in fresh chromite ore processing residue (COPR). Science of the Total Environment, 703, 135075. https://doi.org/10.1016/j.scitotenv.2019.135075

Lu, W., Wang, C., Bai, Y., Xie, C., Zhang, Z., Song, W., & Wang, J. (2024). A novel covalent organic framework for efficient photocatalytic reduction of Cr(VI) and synergistic removal of organic pollutants. Environmental Science: Nano, 11, 229–240. https://doi.org/10.1039/D3EN00734K

Ma, A., Tan, Z., Liu, W., Li, X., Wang, K., Zhang, Y., Jiao, X., Li, J., Yang, Y., & Fu, F. (2024). Construction of visible light active CuS/MoS2 heterojunctions for heightened

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

photoreduction of Cr(VI). Catalysis Science & Technology, 14, 5746–5754. https://doi.org/10.1039/D4CY00598H

Ma, F., Philippe, B., Zhao, B., Diao, J., & Li, J. (2020). Simultaneous adsorption and reduction of hexavalent chromium on biochar-supported nanoscale zero-valent iron (nZVI) in aqueous solution. Water Science and Technology, 82(7), 1339–1349. https://doi.org/10.2166/wst.2020.392

Ma, F., Zhao, H., Zheng, X., Zhang, J., Ding, W., Jiao, Y., Li, Q., & Kang, H. (2024). Green synthesis of nZVI-modified biochar significantly enhanced the removal of Cr(VI) from aqueous solution. Environmental Science and Pollution Research, 31, 33993–34009. https://doi.org/10.1007/s11356-024-33553-x

Ma, L., Chen, N., Feng, C., Yao, Y., Wang, S., Wang, G., Su, Y., & Zhang, Y. (2022). Enhanced Cr(VI) reduction in biocathode microbial electrolysis cell using Fenton-derived ferric sludge. Water Research, 212, 118144. https://doi.org/10.1016/j.watres.2022.118144

Mantel, T., Glass, S., Usman, M., Lyberis, A., Filiz, V., & Ernst, M. (2022). Adsorptive dead-end filtration for removal of Cr(VI) using novel amine modified polyacrylonitrile ultrafiltration membranes. Environmental Science: Water Research & Technology, 8, 2981–2994. https://doi.org/10.1039/D2EW00570K

Mao, W., Zhang, Y., Luo, J., Chen, L., & Guan, Y. (2022). Novel co-polymerization of polypyrrole/polyaniline on ferrate modified biochar composites for the efficient adsorption of hexavalent chromium in water. Chemosphere, 303, 135254. https://doi.org/10.1016/j.chemosphere.2022.135254

Meaza, I., Williams, A. R., Wise, S. S., Lu, H., & Wise, J. P., Sr. (2024). Carcinogenic mechanisms of hexavalent chromium: From DNA breaks to chromosome instability and neoplastic transformation. Current Environmental Health Reports, 11(4), 484–546. https://doi.org/10.1007/s40572-024-00460-9

Mishra, S., & Bharagava, R. N. (2016). Toxic and genotoxic effects of hexavalent chromium in environment and its bioremediation strategies. Journal of Environmental Science and Health, Part C, 34(1), 1–32. https://doi.org/10.1080/10590501.2015.1096883

Mondal, S. K., & Saha, P. (2020). Removal of hexavalent chromium from wastewater using supported liquid membrane: Synthesis of chromium-iron complex through

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

electrochemical reaction. Water and Environment Journal, 34(S1), 753–771. https://doi.org/10.1111/wej.12576

Mortazavian, S., Hunyadi Murph, S. E., & Moon, J. (2022). Biochar nanocomposite as an inexpensive and highly efficient carbonaceous adsorbent for hexavalent chromium removal. Materials, 15(17), 6055. https://doi.org/10.3390/ma15176055

Mu, C., Huang, K., & Wang, L. (2024). Constructed wetland coupled microbial fuel cell with Phragmites australis planted for Cr(VI) removal and electricity generation. Journal of Water Process Engineering, 67, 106238. https://doi.org/10.1016/j.jwpe.2024.106238

Mungan, A. L., Hjelvik, E. A., Straub, A. P., & Korak, J. A. (2024). A hybrid anion exchanger with nanoscale zero valent iron for trace hexavalent chromium removal from drinking water. Environmental Science: Advances, 3, 1598–1615. https://doi.org/10.1039/D4VA00246F

Ouyang, J., Miao, Q., Wei, D., Zhang, X., Luo, E., Li, C., & Wei, L. (2023). Removal of Cr(VI) and microbial community analysis in PCB wastewater treatment based on BESI process. PLOS ONE, 18(8), e0290023. https://doi.org/10.1371/journal.pone.0290023

Pakade, V. E., Tavengwa, N. T., & Madikizela, L. M. (2019). Recent advances in hexavalent chromium removal from aqueous solutions by adsorptive methods. RSC Advances, 9(45), 26142–26164. https://doi.org/10.1039/C9RA05188K

Pakhale, V. D., & Gogate, P. R. (2024). Removal of carcinogenic Cr(VI) from effluent of electroplating industry using adsorptive separation. Environmental Quality Management, 34(2), e22260. https://doi.org/10.1002/tqem.22260

Park, J. E., Shin, J.-H., Oh, W., Choi, S.-J., Kim, J., Kim, C., & Jeon, J. (2022). Removal of hexavalent chromium(VI) from wastewater using chitosan-coated iron oxide nanocomposite membranes. Toxics, 10(2), 98. https://doi.org/10.3390/toxics10020098

Pereira, A. C. (2026a). Controlling co-precipitation in hydrometallurgy: From physicochemical parameters to process design and technology readiness. IKR Journal of Engineering and Technology, 2(3), 46–77. https://doi.org/10.5281/zenodo.20357561

Pereira, A. C. (2026b). Conventional ion-exchange and chelating resins for metal recovery: A critical comparison of selectivity, dynamic performance, regeneration, and process integration. International Journal of Current Science Research and Review, 9(9), 4916–4945. https://doi.org/10.47191/ijcsrr/V9-i9-08

Pereira, A. C. (2026c). Improving filterability of hydroxide precipitates in hydrometallurgical hydrolysis processes: A critical review. IKR Journal of Engineering and Technology, 2(3), 21–45. https://doi.org/10.5281/zenodo.20098962

Punia, S., Wu, L., & Khodadoust, A. P. (2021). Adsorption of hexavalent chromium from water using manganese-aluminum coated sand: Kinetics, equilibrium, effect of pH and ionic

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

strength. Journal of Environmental Science and Health, Part A, 56(3), 334–345. https://doi.org/10.1080/10934529.2021.1877513

Qin, L., He, L., Yang, W., & Lin, A. (2020). Preparation of a novel iron-based biochar composite for removal of hexavalent chromium in water. Environmental Science and Pollution Research, 27(9), 9214–9226. https://doi.org/10.1007/s11356-019-06954-6

Rajapaksha, A. U., Selvasembian, R., Ashiq, A., Gunarathne, V., Ekanayake, A., Perera, V. O., Wijesekera, H., Mia, S., Ahmad, M., Vithanage, M., & Ok, Y. S. (2022). A systematic review on adsorptive removal of hexavalent chromium from aqueous solutions: Recent advances. Science of the Total Environment, 809, 152055. https://doi.org/10.1016/j.scitotenv.2021.152055

Rajoria, S., Vashishtha, M., & Sangal, V. K. (2024). Electroplating wastewater treatment by electro-oxidation using synthesized new electrode: Experimental, optimization, kinetics, and cost analysis. Process Safety and Environmental Protection, 183, 735–756. https://doi.org/10.1016/j.psep.2024.01.023

Rajput, M. K., Konwar, M., & Sarma, D. (2021). Preparation of a novel environmentally friendly hydrophobic deep eutectic solvent ChCl-THY and its application in removal of hexavalent chromium from aqueous solution. Water Environment Research, 93(10), 2250–2260. https://doi.org/10.1002/wer.1597

Ramli, N. N., Othman, A. R., Kurniawan, S. B., Sheikh Abdullah, S. R., & Abu Hasan, H. (2023). Metabolic pathway of Cr(VI) reduction by bacteria: A review. Microbiological Research, 268, 127288. https://doi.org/10.1016/j.micres.2022.127288

Ren, S., Wang, Y., Han, Z., Zhang, Q., & Cui, C. (2022). Synthesis of polydopamine modified MgAl-LDH for high efficient Cr(VI) removal from wastewater. Environmental Research, 215, 114191. https://doi.org/10.1016/j.envres.2022.114191

Rodrigues, L. A., Maschio, L. J., da Silva, R. E., & da Silva, M. L. C. P. (2010). Adsorption of Cr(VI) from aqueous solution by hydrous zirconium oxide. Journal of Hazardous Materials, 173(1–3), 630–636. https://doi.org/10.1016/j.jhazmat.2009.08.131

Sangkarak, S., Phetrak, A., Kittipongvises, S., Kitkaew, D., Phihusut, D., & Lohwacharin, J. (2020). Adsorptive performance of activated carbon reused from household drinking water filter for hexavalent chromium-contaminated water. Journal of Environmental Management, 272, 111085. https://doi.org/10.1016/j.jenvman.2020.111085

Sassi, W., Boubaker, H., Ben-Khaled, H., Dhaoui, S., Ghorbal, A., & Hihn, J.-Y. (2021). Modelization and implementation of free adsorption and electrosorption of Cr(VI) from wastewater using Al2O3 nanoparticles: Assessment and comparison of the two

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

processes. Environmental Science and Pollution Research, 28, 28349–28366. https://doi.org/10.1007/s11356-021-12612-7

Shen, W., Gao, Y., Liu, Z., Zhang, X., Quan, F., Peng, X., Wang, X., Li, J., Qin, Z., He, Y., & Li, H. (2024). Enhanced Fe(II)/Fe(III) cycle by boron enabled efficient Cr(VI) removal with microscale zero-valent iron. RSC Advances, 14, 6719–6726. https://doi.org/10.1039/D3RA08163J

Shi, K., Zhang, Y., Ding, G., Wang, X., Yan, X., Pan, H., & Zhao, Y. (2023). Remediation of Cr(VI)-contaminated soil mixed with chromite ore processing residue by ferrous sulfate and enzyme residue. Science of the Total Environment, 892, 164743. https://doi.org/10.1016/j.scitotenv.2023.164743

Singh, S., Naik, T. S. S. K., Anil, A. G., Khasnabis, S., Nath, B., U, B., Kumar, V., Garg, V. K., Subramanian, S., Singh, J., & Ramamurthy, P. C. (2022). A novel CaO nanocomposite cross linked graphene oxide for Cr(VI) removal and sensing from wastewater. Chemosphere, 301, 134714. https://doi.org/10.1016/j.chemosphere.2022.134714

Singh, V., Singh, N., Verma, M., Kamal, R., Tiwari, R., Chivate, M. S., Rai, S. N., Kumar, A., Singh, A., Singh, M. P., Vamanu, E., & Mishra, V. (2022). Hexavalent-chromium-induced oxidative stress and the protective role of antioxidants against cellular toxicity. Antioxidants, 11(12), 2375. https://doi.org/10.3390/antiox11122375

Sinha, R., Kumar, R., Sharma, P., Kant, N., Shang, J., & Aminabhavi, T. M. (2022). Removal of hexavalent chromium via biochar-based adsorbents: State-of-the-art, challenges, and future perspectives. Journal of Environmental Management, 317, 115356. https://doi.org/10.1016/j.jenvman.2022.115356

Song, L., Su, C., Li, H., Zhao, H., & Chen, R. (2025). Round-the-clock Cr(VI) removal from actual industrial electroplating wastewater over Bi2S3/PDA/PEI under natural conditions: Synergism adsorption and photocatalysis. Chemical Engineering Journal, 509, 161607. https://doi.org/10.1016/j.cej.2025.161607

Stern, C. M., Abeythunga, M. M., & Elgrishi, N. (2024). Advancing Cr(VI) electroreduction: A redox mediator to catalyze chromium remediation. ACS Organic & Inorganic Au, 4(1), 113–119. https://doi.org/10.1021/acsorginorgau.3c00034

Stern, C. M., Jegede, T. O., Hulse, V. A., & Elgrishi, N. (2021). Electrochemical reduction of Cr(VI) in water: Lessons learned from fundamental studies and applications. Chemical Society Reviews, 50, 1642–1667. https://doi.org/10.1039/D0CS01165G

Stern, C. M., Meche, D. D., & Elgrishi, N. (2022). Impact of choice of buffer on electrochemical reduction of Cr(VI) in water on carbon electrodes. RSC Advances, 12, 32592–32599. https://doi.org/10.1039/D2RA05943F

Sun, P., Wang, Z., An, S., Zhao, J., Yan, Y., Zhang, D., Wu, Z., Shen, B., & Lyu, H. (2022). Biochar-supported nZVI for the removal of Cr(VI) from soil and water: Advances in

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

experimental research and engineering applications. Journal of Environmental Management, 316, 115211. https://doi.org/10.1016/j.jenvman.2022.115211

Sun, Y., Li, L., He, J., & Lei, Y. (2025). Waste control by waste: Metals recovery from electroplating sludge via a chlorination roasting followed by silicothermic reduction using solar-grade silicon cutting waste. Waste Management, 194, 125–136. https://doi.org/10.1016/j.wasman.2024.12.036

Tan, C., Avasarala, S., & Liu, H. (2020). Hexavalent chromium release in drinking water distribution systems: New insights into zerovalent chromium in iron corrosion scales. Environmental Science & Technology, 54(20), 13036–13045. https://doi.org/10.1021/acs.est.0c03922

Tan, X., Yang, J., Shaaban, M., Cai, Y., Wang, B., & Peng, Q.-A. (2023). Cr(VI) removal from wastewater using nano zero-valent iron and chromium-reducing bacteria. Environmental Science and Pollution Research, 30, 113323–113334. https://doi.org/10.1007/s11356-023-30292-3

Tang, X., Huang, Y., Li, Y., Wang, L., Pei, X., Zhou, D., He, P., & Hughes, S. S. (2021). Study on detoxification and removal mechanisms of hexavalent chromium by microorganisms. Ecotoxicology and Environmental Safety, 208, 111699. https://doi.org/10.1016/j.ecoenv.2020.111699

Tao, X., Hu, X., Wen, Z., Ming, Y., Li, J., Liu, Y., & Chen, R. (2022). Highly efficient Cr(VI) removal from industrial electroplating wastewater over Bi2S3 nanostructures prepared by dual sulfur-precursors: Insights on the promotion effect of sulfate ions. Journal of Hazardous Materials, 424, 127423. https://doi.org/10.1016/j.jhazmat.2021.127423

Tejada-Tovar, C. N., Villabona-Ortíz, A., & Ortega-Toro, R. (2020). Cr(VI) biosorption: Effect of temperature, particle size and bed height. Revista Facultad de Ingeniería Universidad de Antioquia, 96, 78–86. https://doi.org/10.17533/udea.redin.20191149

Thiripelu, P., Manjunathan, J., Revathi, M., & Ramasamy, P. (2024). Removal of hexavalent chromium from electroplating wastewater by ion-exchange in presence of Ni(II) and Zn(II) ions. Journal of Water Process Engineering, 58, 104815. https://doi.org/10.1016/j.jwpe.2024.104815

Tian, H., Liu, P., Sun, H., & Huang, X. (2024). Efficient one-step removal and immobilization of recalcitrant Cr(III) and Cr(VI) fractions in real electroplating wastewater using electrolysis with O2 aeration. Journal of Water Process Engineering, 65, 105783. https://doi.org/10.1016/j.jwpe.2024.105783

Tian, Y., Sun, X., Chen, N., Cui, X., Yu, H., Feng, Y., Xing, D., & He, W. (2024). Efficient removal of hexavalent chromium from wastewater using a novel sodium alginate-biochar composite adsorbent. Journal of Water Process Engineering, 64, 105655. https://doi.org/10.1016/j.jwpe.2024.105655

Tie, J., Li, W., Duan, X., Wang, H., Liu, S., & Zhao, W. (2024). Magnetic iron-based waterworks sludge modified by chitosan and FeS for aqueous Cr(VI) adsorption and reduction. RSC Advances, 14, 28915–28926. https://doi.org/10.1039/D4RA02852J

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Tie, J., Zhang, M., Shen, C., Liu, H., & Du, C. (2023). Preparation of Ce/ferroferric oxide/food waste-derived biochar for aqueous Cr(VI) adsorption. Journal of Chemical Technology & Biotechnology, 98, 168–178. https://doi.org/10.1002/jctb.7232

Ukhurebor, K. E., Aigbe, U. O., Onyancha, R. B., Nwankwo, W., Osibote, O. A., Paumo, H. K., Ama, O. M., Adetunji, C. O., & Siloko, I. U. (2021). Effect of hexavalent chromium on the environment and removal techniques: A review. Journal of Environmental Management, 280, 111809. https://doi.org/10.1016/j.jenvman.2020.111809

Verma, N., Chundawat, T. S., Surolia, P. K., & Vaya, D. (2022). Photocatalytic reduction of Cr(VI) by TiO2/GO nanocomposite. ChemistrySelect, 7, e202201275. https://doi.org/10.1002/slct.202201275

Villabona-Ortíz, A., Tejada-Tovar, C., & Contreras-Amaya, R. (2021). Electrocoagulation as an alternative for the removal of chromium(VI) in solution. Tecnura, 25(68), 28–42. https://doi.org/10.14483/22487638.17088

Villabona-Ortíz, A., Tejada-Tovar, C., González-Delgado, A. D., Negrete-Palacio, A., & López-Genes, J. (2024). Equilibrium and thermodynamics of chromium(VI) adsorption on inert biomasses of Dioscorea rotundata and Elaeis guineensis. Ciencia e Ingeniería Neogranadina, 34(1), 212–220. https://doi.org/10.19053/01217488.v15.n1.2024.15494

Wan, J., Yu, M., Bi, W., Sun, Y., Wang, W., Hou, Y., Xie, S., Li, T., & Fan, Y. (2024). Research on chromium removal mechanism by electrochemical method from wastewater. Journal of Water Process Engineering, 68, 106447. https://doi.org/10.1016/j.jwpe.2024.106447

Wan, Y., Gao, K., Pan, Z., Zhao, T., & Cheng, Q. (2024). Constructing TiO2@MOF S-scheme heterojunctions for enhanced Cr(VI) photoreduction. Dalton Transactions, 53, 12370–12380. https://doi.org/10.1039/D4DT00831F

Wang, H., Liu, X., & Zhang, Z. (2024). Approaches for electroplating sludge treatment and disposal technology: Reduction, pretreatment and reuse. Journal of Environmental Management, 349, 119535. https://doi.org/10.1016/j.jenvman.2023.119535

Wang, H., Yu, Y., Hu, J., & Wang, H. (2024). A novel method for effective solidifying chromium and preparing crude stainless steel from multi-metallic electroplating sludge. Journal of Hazardous Materials, 465, 133068. https://doi.org/10.1016/j.jhazmat.2023.133068

Wang, Q., Zhao, Y., Liu, Y., Zhang, C., Bamanu, B., Wu, Y., Chao, C., Liu, Y., Tong, Y., & Nuramkhaan, M. (2024). Recovery mechanism of bio-promoters on Cr(VI) suppressed denitrification: Toxicity remediation and enhanced electron transmission. Water Research, 252, 121230. https://doi.org/10.1016/j.watres.2024.121230

Wang, S., Zhong, D., Xu, Y., & Zhong, N. (2021). Polyethylene glycol-stabilized bimetallic nickel–zero valent iron nanoparticles for efficient removal of Cr(VI). New Journal of Chemistry, 45, 13969–13978. https://doi.org/10.1039/D1NJ03122H

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Wang, Y., Xu, Y., Lin, S., Liu, W., & Wang, Y. (2022). Recycling of chromium electroplating sludge using combined calcination-hydrothermal treatment. Surfaces and Interfaces, 29, 101750. https://doi.org/10.1016/j.surfin.2022.101750

Whitaker, A. H., Peña, J., Amor, M., & Duckworth, O. W. (2018). Cr(VI) uptake and reduction by biogenic iron (oxyhydr)oxides. Environmental Science: Processes & Impacts, 20(7), 1056–1068. https://doi.org/10.1039/C8EM00149A

Wu, G., Sun, Y., Xiao, Y., Qin, Y., & Liu, W. (2026). Mechanical ball-milled fulvic acid-modified zero-valent iron: Enhanced electron transport for Fe(III)/Fe(II) cycling and Cr(VI) removal. Environmental Research, 302, 124678. https://doi.org/10.1016/j.envres.2026.124678

Wu, J., Yan, M., Lv, S., Yin, W., Bu, H., Liu, L., Li, P., Deng, H., & Zheng, X. (2021). Preparation of highly dispersive and antioxidative nano zero-valent iron for removal of hexavalent chromium. Chemosphere, 262, 127733. https://doi.org/10.1016/j.chemosphere.2020.127733

Wu, Y., Yang, F., Zhao, H., Xu, Z., & Zhang, Q. (2025). Efficient recovery of valuable metals from electroplating sludge smelting soot via a combined alkali roasting and acid-free aluminum salts leaching methods. Waste Management, 192, 102–113. https://doi.org/10.1016/j.wasman.2024.11.038

Xie, S., Yang, K., Zhang, S., Chen, J., Zhao, J., & Zhu, L. (2025). Enhanced oxidation of Cr(III) with the mineral transformation of CrxFe1-x(OH)3 in the presence of Mn(II): Overlooked process during the reoccurrence of Cr(VI) in reduced chromite ore processing residue. Environmental Pollution, 375, 126327. https://doi.org/10.1016/j.envpol.2025.126327

Xiong, W., Tian, K., Liu, S., Li, M., & Zhu, Y. (2025). TEPA modified magnetic cellulose nanocrystals for efficient and highly selective removal of Cr(VI) from electroplating wastewater by high-density amine-based sites. Journal of Colloid and Interface Science, 685, 1195–1208. https://doi.org/10.1016/j.jcis.2025.01.209

Xu, H., Ren, L., Qin, C., Zhang, H., Li, X., & Zhao, Y. (2024). New insights on zero-valent iron permeable reactive barrier for Cr(VI) removal: Function of FeS reaction zone downstream in-situ generated by sulfate-reducing bacteria. Journal of Hazardous Materials, 480, 136282. https://doi.org/10.1016/j.jhazmat.2024.136282

Yang, W.-M., Liu, F., Jin, Y.-T., Dong, Z.-M., & Zhao, G.-C. (2022). Efficient reduction of Cr(VI) with carbon quantum dots. ACS Omega, 7(27), 23555–23565. https://doi.org/10.1021/acsomega.2c02063

Yang, X., Zhao, Z., Zhang, G., Hirayama, S., Nguyen, B. V., Lei, Z., Shimizu, K., & Zhang, Z. (2021). Insight into Cr(VI) biosorption onto algal-bacterial granular sludge. Journal of Hazardous Materials, 414, 125479. https://doi.org/10.1016/j.jhazmat.2021.125479

Yao, F., Jia, M., Yang, Q., Luo, K., Chen, F., Zhong, Y., He, L., Pi, Z., Hou, K., Wang, D., & Li, X. (2020). Electrochemical Cr(VI) removal from aqueous media using titanium as anode: Simultaneous indirect electrochemical reduction and in-situ precipitation of

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

Cr(III). Chemosphere, 260, 127537. https://doi.org/10.1016/j.chemosphere.2020.127537

Ye, J., Wang, Y., Xu, Q., Wu, H., Tong, J., & Shi, J. (2021). Removal of hexavalent chromium from wastewater by Cu/Fe bimetallic nanoparticles. Scientific Reports, 11, 10848. https://doi.org/10.1038/s41598-021-90414-0

Yin, Z., Xu, S., Liu, S., Xu, S., Li, J., & Zhang, Y. (2020). A novel magnetic biochar prepared by K2FeO4-promoted oxidative pyrolysis of pomelo peel for adsorption of hexavalent chromium. Bioresource Technology, 300, 122680. https://doi.org/10.1016/j.biortech.2019.122680

Yu, C., & Liao, Y. (2023). Removal of Cr(VI) ions from wastewater by Fe3O4-loaded porous sludge biochar. Water Science and Technology, 88(4), 947–960. https://doi.org/10.2166/wst.2023.244

Yu, C., & Yang, J. (2024). Removal of Cr(VI) in wastewater by Fe–Mn oxide loaded sludge biochar. RSC Advances, 14, 11746–11757. https://doi.org/10.1039/D4RA00169A

Yuan, X., Li, J., Luo, L., Zhong, Z., & Xie, X. (2023). Advances in sorptive removal of hexavalent chromium (Cr(VI)) in aqueous solutions using polymeric materials. Polymers, 15(2), 388. https://doi.org/10.3390/polym15020388

Zhang, D., Liu, X., Guo, D., Li, G., Qu, J., & Dong, H. (2022). Cr(VI) reduction by siderophore alone and in combination with reduced clay minerals. Environmental Science & Technology, 56(17), 12315–12324. https://doi.org/10.1021/acs.est.2c04104

Zhang, Y., Xu, X., Yue, C., Song, L., Lv, Y., Liu, F., & Li, A. (2021). Insight into the efficient co-removal of Cr(VI) and Cr(III) by positively charged UiO-66-NH2 decorated ultrafiltration membrane. Chemical Engineering Journal, 404, 126546. https://doi.org/10.1016/j.cej.2020.126546

Zhao, N., Zhang, Y., Liu, M., Peng, Y., & Liu, J. (2022). 2D–2D WO3–Bi2WO6 photocatalyst with an S-scheme heterojunction for highly efficient Cr(VI) reduction. CrystEngComm, 24, 6902–6909. https://doi.org/10.1039/D2CE01024K

Zhou, N., Gong, K., Hu, Q., Cheng, X., Zhou, J., Dong, M., Wang, N., Ding, T., Qiu, B., & Guo, Z. (2020). Optimizing nanocarbon shell in zero-valent iron nanoparticles for improved electron utilization in Cr(VI) reduction. Chemosphere, 242, 125235. https://doi.org/10.1016/j.chemosphere.2019.125235

Zhuang, X., Tang, S., Dong, W., Xin, F., Jia, H., & Wu, X. (2023). Improved performance of Cr(VI)-reducing microbial fuel cells by nano-FeS hybridized biocathodes. RSC Advances, 13, 6768–6778. https://doi.org/10.1039/D3RA00683B

Conselho Nacional do Meio Ambiente [CONAMA]. (2011). Resolução CONAMA nº 430, de 13 de maio de 2011: Condições e padrões de lançamento de efluentes. https://conama.mma.gov.br/index.php?id=18684&option=com_sisconama&task=documento.download

JIRRS
Journal International Review of Research Studies

Received: 12/06/2026 - **Accepted:** 08/09/2026
Vol: 01.02
DOI: 10.66104/sg80e018
Pages: 1-44

U.S. Environmental Protection Agency. (1994). Method 218.6: Determination of dissolved hexavalent chromium in drinking water, groundwater, and industrial wastewater effluents by ion chromatography. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1013FD7.txt

U.S. Environmental Protection Agency. (n.d.-a). Hexavalent chromium: Questions and answers. https://www.epa.gov/cwa-methods/hexavalent-chromium-questions-and-answers

U.S. Environmental Protection Agency. (n.d.-b). Chromium in drinking water. https://www.epa.gov/sdwa/chromium-drinking-water

World Health Organization. (2026). Guidelines for drinking-water quality: Fourth edition incorporating the first, second and third addenda. https://www.who.int/publications/i/item/9789240121225