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REVIEW

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Chromium in the Environment: Sources, Speciation, Geochemistry and Toxicity

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Abstract

Chromium is a widely utilized industrial metal that has emerged as a major hazardous pollutant in soil and water, largely due to its extensive release from mining, electroplating, tanning, steel production, textile industry, and other anthropogenic activities. In soil, Cr primarily exists in two forms: trivalent Cr(III) and hexavalent Cr(VI). The speciation of Cr depends on soil pH, redox potential, organic matter content, and microbial activity; these factors, in turn, govern its mobility, bioavailability, and toxicity. Being highly soluble, mobile, and bioavailable, Cr(VI) exposure in plants leads to severe phytotoxicity, reduced crop yields, and oxidative stress. Furthermore, through its entry into the food chain, as well as via exposure to contaminated air and water, Cr poses a carcinogenic risk to humans. This review summarizes current knowledge regarding various sources of Cr (both natural and anthropogenic), chromium speciation and its chemistry in soil, and its environmental impacts.

Keywords: Heavy metal; Chromium; Speciation; Toxicity; Environmental pollution

Introduction

Heavy metal contamination in soil and water has raised concerns about environmental pollution worldwide. Rapid economic growth increases environmental pollution through the extensive use of heavy metals. These contaminants enter the food chain and cause significant harm to ecosystems, including human health (Kumar and Aery, 2016; Paul et al., 2024). The untreated disposal of hazardous and harmful industrial waste, often containing toxic heavy metals, into natural habitats is contributing to increasing environmental pollution worldwide (Mishra and Bharagava, 2018). Heavy metals and metalloids do not decompose easily and persist for long periods in the biosphere. Industrial waste, acid mine drainage, solid waste dumps, agricultural runoff, acid rain, weathering, factory drainage, poorly managed landfills, metal leaching, biomedical waste, and microplastics increase the entry of heavy metals into the environment. Industrial waste contains heavy metals such as chromium, mercury, cadmium, lead, and arsenic, as well as other metals like silver, iron, and manganese. Heavy metals cause various biological and physiological problems in humans, including acute and chronic toxicity (Prasad et al., 2021; Paul et al., 2024; Choudhary and Kumar, 2024). Heavy metal pollution disrupts plant growth and physiology by inducing toxicity, ionic imbalance, and oxidative stress, thereby affecting plant development and productivity (Kumar and Aery, 2016).

Chromium, a transition metal, is the 21st most abundant element on Earth and is obtained from chromite ore (Paul et al., 2024). The element Cr was identified in 1797 as a constituent of the mineral crocoite ($PbCrO_4$) (Ali et al., 2023). It is naturally occurring in high quantities in the Earth's crust. Cr is one of the most important heavy metal pollutants in the environment because it is extensively used in industrial processes. Cr is processed in high amounts in South Africa, Kazakhstan, Turkey, and India. In India, it is processed in Chhattisgarh, Gujarat, Andhra Pradesh, Odisha, and West Bengal (Paul et al., 2024). The concentration of Cr in the environment is continuously increasing due to its processing and industrial use. Chromium is also considered an essential trace element for humans, but excessive exposure to it can cause harmful and adverse health effects in humans and animals. It also interferes with plant metabolism, reducing crop growth and yields, and reducing the quality of vegetables and grains (Prasad et al., 2021). Chromium pollution is a serious environmental pollutant that contaminates natural resources, especially water and soil.

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The tolerable limit for Cr in soil for human and environmental health is approximately 64 mg kg^{-1} (Ali et al., 2023). Chromium concentrations in the Pali Industrial Area of Rajasthan ranged from 40 to 240 mg kg^{-1}, with an average of 154.8 mg kg^{-1}. This is much higher than the normal soil chromium concentration of 100 mg kg^{-1} (Krishna and Govil, 2004).

Sources of Chromium in the Environment

Chromium, a naturally occurring heavy metal, enters the soil, water, and air through both natural and anthropogenic (human-made) sources, thereby causing pollution. To assess and control Cr pollution, it is important to distinguish between these natural and anthropogenic sources.

Natural Sources of Chromium

Geologically, chromium comes from mafic and ultramafic rocks that contain chromite. Cr(III) is released by weathering processes that are aided by microbes or geological interactions, which can then oxidize to become Cr(VI) (Tumolo et al., 2020). The naturally high chromium content of ultramafic and serpentine-derived soils contributes to higher background chromium concentrations in soil and groundwater (Poznanovic Spahic et al., 2019). Chromium is naturally stored in the environment in volcanic dust, rocks, and general lithospheric materials (Sharma et al., 2022). The oxidative weathering processes within catchment regions can also carry chromium into rivers and sediments (Perraki et al., 2021). The sources and distribution of Cr in the environment are given in Fig. 1.

Anthropogenic Sources of Chromium

In densely populated areas, human activities leading to chromium contamination in rivers pose a risk to living organisms (Oliveira et al., 2026). The most severe pollution associated with Cr(VI) is from industrial activities. These activities include the refining of chromite ore, the production of ferrochrome and stainless steel, electroplating, leather tanning, the manufacture of pigments and dyes, wood preservation, as well as operations within the chemical and textile industries (Coetzee et al., 2020; Tumolo et al., 2020). The combustion of coal and oil, waste incineration, and fly ash emissions from power plants also release chromium into the air, soil, and water. Industrial wastewater and solid waste, the disposal of chromium-bearing residues in landfills, and leachate runoff from waste sites constitute the primary pathways through which Cr(VI) enters groundwater and surface water (Kazakis et al., 2018). In agricultural areas, agricultural inputs such as phosphorus and nitrogen fertilizers act as anthropogenic sources of chromium and can influence the accumulation and mobility of Cr(VI) in soils and aquifers (Perraki et al., 2021; Ullah et al., 2023).

Industrial Activities

The primary anthropogenic sources of chromium pollution in soil and water are industrial processes, including metallurgy, refractory production, the chemical industry, and the leather industry. These sectors discharge over 170,000 tons of chromium annually in the form of waste, leading to the progressive pollution of soil and water bodies (Hussain and Memon, 2020). Chromium is naturally found in the environment as Cr (III), while the primary source of Cr(VI) is industrial activity (Kimbrough et al., 1999). Agriculture and industrial activities such as electroplating, tanneries, paint and dye industries, metal plating, cement and steel plants, wood processing, papermaking, and leaching processes use a lot of Cr, which is the main cause of Cr loss from soil and water (Ali et al., 2023). Hexavalent chromium contamination includes waste generated by industrial applications such as tanning, paper pulp production, electroplating, petroleum refining, and industrial water cooling (Saha et al., 2011). About 84% of chromium is extracted from the energy sector, 11% from wastewater management, 3% from the metal industry, 2% from the chemical industry, and a minimal amount, 1%, from the mineral industry. Tobacco smoke, coal burning, and automatic catalytic converters are also sources of Cr in the environment (Paul et al., 2024). Sodium chromate is produced by the oxidation of ferrous chromite ($FeCr_2O_4$) using a less lime-intensive low-lime or no-lime process. This produces dichromate, chromic oxide, chromic acid, and other chromate compounds, and the reduction of chromite ore produces chromium alloys and other chemicals (Kimbrough et al., 1999). Chromium is mainly used for metallurgical, refractory, and chemical purposes, accounting for 67%, 18%, and 15% of chromium production, respectively (Saha et al., 2011). In the United States, approximately 70% of chromium is used in metal alloys (stainless and heat-resistant steel). In comparison, 10–15% is used as chromium (VI) chemicals in metal plating, dyes, paint pigments, and leather tanning (Kimbrough et al., 1999). Industrial activities, such as metallurgy, which rely on specific processes and treatment methods for stainless steel production and other metal finishing operations, discharge chromium-bearing waste and wastewater containing Cr(VI) or Cr(III), thereby contributing to chromium pollution (Ciavatta et al., 2012). The disposal of industrial and urban waste also contributes to chromium pollution in soil and water. The chromium contamination resulting from these sources frequently leads to elevated concentrations of Cr in surface and subsurface soils, as well as in surface water and groundwater (Ritter, 2002; Kamaludeen et al., 2003).

Decorative or hard chrome plating is a method of using hexavalent chromium to create a rust-resistant, shiny, and hard layer on plastic and metal products (such as car bumpers, shower heads, and machine parts). Hexavalent and trivalent chrome-plating baths are widely used, with up to 35% of the trivalent/hexavalent chromium being removed as waste (Saha et al., 2011). Iron alloys are less harmful because the Cr in them is in the zero-oxidation state and is insoluble. Cr can be recycled by oxidizing Cr from stainless steel (Kimbrough et al., 1999). Paint pigments (such as chromium orange, yellow, red, zinc green/yellow), waterproof adhesives, textile dyes, automobile paints, photography, and oxidants and analytical standards in chemical labs (such as potassium dichromate) all contain chromium compounds. Lead, zinc, and barium chromates are toxic and pollute the environment by leaching into wastewater from labs and industries in the form of trivalent and hexavalent chromium (Saha et al., 2011).

The process of converting rawhide into leather is called 'tanning'. Chrome sulphate (tanning powder) is used in chrome tanning. It binds the collagen polypeptide chains together, transforming them into a helical form, preventing water from penetrating the pores of the leather, and making the leather more thermostable. Chrome tanning releases up to 40% of chromium into wastewater in the form of hexavalent and trivalent chromium (Saha et al., 2011). The leather industry constitutes a significant source of chromium pollution; while by-products of the leather manufacturing process are utilized in organic fertilizers, the Cr present in the waste generated by tanneries contaminates the soil (Ciavatta et al., 2012). The illicit burial of waste from tanneries results in the contamination of fertile agricultural land with chromium, along with other heavy metals and hydrocarbons. The occurrence of chromium and copper contamination in regions characterized by volcanic soils, stemming from the activities of the leather industry, underscores the far-reaching environmental impact of this sector (Caporale et al., 2019). Industrial facilities (such as those operated by the Department of Energy) have inadvertently created contaminated sites where chromium and other toxic metals continue to pose persistent environmental and health risks (Stewart et al., 2003).

Mining and Metallurgical Processes

Activities associated with mining and metallurgy are the primary causes of chromium pollution (Khatua and Kumar, 2023). Waste residues from chromite ore processing persist in soil and groundwater for extended periods and serve as sources of Cr(VI) contamination (Tiwary et al., 2005). Mineral fertilizers derived from mining operations may also contain chromium, the application of which leads to soil pollution (Ciavatta et al., 2012). Inadequate waste management practices allow waste generated during chromite ore processing to release chromium into the environment. Untreated pre-tanning waste discharged from mining and metallurgical processes also constitutes a source of chromium pollution (Bhattacharya et al., 2020). Chromium is present in excessive quantities in the air, soil, and groundwater surrounding ferro-alloy manufacturing facilities; furthermore, chromium pollution steadily escalates due to the erosion and runoff of chromite-bearing materials (Wang et al., 2011).

The Sukinda Valley (Valley of Despair) in Jajpur, Odisha, holds approximately 98% of India's chromite reserves and has a production rate of 334 million tonnes. Due to high chromium concentrations in groundwater, soil, sediments, and air, this region is prone to pollution, and exposure to these has been observed to have adverse effects on the health of residents living in the vicinity. Approximately 1.8 lakh mining workers and residents are affected annually by inhalation, ingestion, and skin exposure to Cr (Mohanty et al., 2023). Chromium-laden waste generated by metallurgical processes, specifically those involved in the production of steel, alloys, and refractory materials, pollutes the environment; consequently, proper management of this waste is essential to mitigate such pollution (Ciavatta et al., 2012). Mining activities exacerbate chromium pollution in the environment by disturbing natural geological formations that are rich in chromium (Das et al., 2021). Sludge and solid residues generated by mining and metallurgical operations lead to the progressive accumulation of chromium in soil and sediments (Nunes et al., 2021).

Agriculture Runoff

The use of chromium-containing substances in agriculture, along with the runoff of contaminated water, contributes to chromium pollution. In organic fertilizers derived from by-products of the leather industry, chromium is primarily present in the Cr(III) form. These generally pose a low environmental risk because the mobility and toxicity associated with this oxidation state are low; consequently, they are applied to agricultural lands (Alengebawy et al., 2021). Due to the potential for toxicity and environmental contamination, the use of Cr(VI)-containing substances in agriculture has been prohibited. Municipal solid waste and sewage sludge, which are utilized as soil amendments in agricultural lands, can serve as sources of chromium pollution (Nunes et al., 2021). Over time, the continuous application of chromium-containing fertilizers and soil amendments to agricultural lands leads to the accumulation of chromium at high concentrations (Ciavatta et al., 2012). In industrial wastewater used for agricultural irrigation, the chemical form and concentration of chromium depend on the source of the wastewater and the extent of its treatment (Ertani et al., 2017). Runoff water from fields treated with chromium-containing substances acts as a vehicle, transporting Cr into water bodies and groundwater systems (Ciavatta et al., 2012). The mobility of chromium in agricultural soils is influenced by soil properties such as pH, organic matter content, and redox conditions, which determine whether the chromium is retained within the soil or leached away (Ertani et al., 2017). Elevated chromium concentrations in agricultural soils are primarily attributed to anthropogenic activities, such as the use of contaminated soil amendments and irrigation with polluted water (Sezgin et al., 2023).

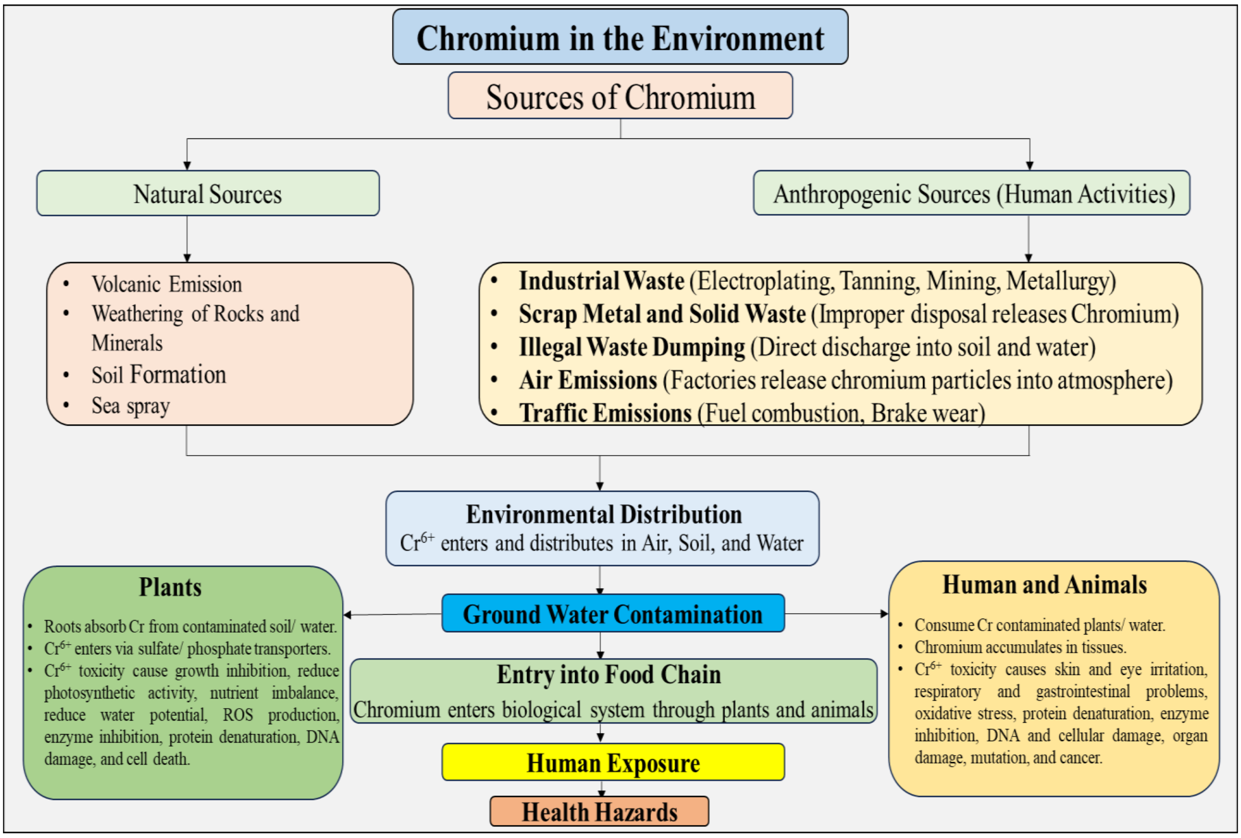

Fig. 1. Chromium in the Environment: Sources, Distribution, and the Effects of Cr on Plants, Animals, and Humans.

Speciation and Soil Chemistry of Chromium

Chromium Speciation

Chromium-containing compounds are multicoloured, and Cr can exist in various oxidation states ranging from −2 to +6. Compounds containing Cr exhibit a variety of geometric structures, including square planar, tetrahedral, and octahedral (Shupack, 1991). Cr occurs naturally as chromite ore ($FeCr_2O_4$) in serpentine and ultramafic rocks in the +3 state, as well as in association with other minerals such as Crocoite, Terapacite, Bentorite, and Vauquelinite (Oliveira, 2012). The metallic form Cr(0), trivalent Cr(III), and hexavalent Cr(VI) oxidation states are the most stable states of chromium. Cr(0) is solid and, due to its high fusion potential, is used in industry to make steel and other alloys (Oliveira, 2012). Hexavalent chromium Cr(VI) occurs as chromate, dichromate, and CrO_3 and is more soluble, while trivalent chromium Cr(III) occurs as sulphate, oxide, or hydroxide and is less soluble (Bagchi et al., 2002).

In environmental systems, both the trivalent and hexavalent forms of chromium exhibit distinct chemical properties and environmental behaviors (Gorny et al., 2016). In soils with a pH above 5, the low mobility of Cr(III) allows it to be readily immobilized via processes such as precipitation and adsorption. Conversely, Cr(VI) exists as oxy-anions, specifically chromate (CrO_4^{2-}) and dichromate ($Cr_2O_7^{2-}$), which are highly soluble in water and significantly more mobile within soil and groundwater environments (Ciavatta et al., 2012). Chromium speciation is contingent upon pH and redox potential. Furthermore, both chemical and microbial transformations, including oxidation/reduction, precipitation/dissolution, and adsorption/desorption, govern chromium's environmental behavior (Fig. 2).

Cr(VI) functions as a potent oxidizing agent and, under oxygenated conditions, is readily reduced by accepting electrons from electron donors such as Fe(II) and organic matter (Kamaludeen et al., 2003). The bioavailability of chromium is influenced by the interconversion of its various species; for instance, Cr(VI) tends to adsorb onto positively charged surfaces, whereas Cr(III) precipitates as a hydroxide and adsorbs more strongly in the presence of high pH levels and elevated concentrations of organic matter (Stewart et al., 2003). Chromium speciation varies significantly depending on the specific soil type and oxidation state; for example, under acidic conditions, the presence of organic matter and Fe(II) accelerates the reduction of Cr(VI) to Cr(III) (Stewart et al., 2003).

Naturally, the oxidation of Cr(III) to Cr(VI) is relatively rare; however, in the presence of strong oxidants such as manganese oxides, alkaline pH conditions, low organic matter content, and high redox potential, the oxidation of Cr(III) to Cr(VI) does occur (Ciavatta et al., 2012). Chromium is also found associated with iron oxides, chromite, and heavy minerals, which govern the behavior of chromium release in contaminated soils (Bhattacharya et al., 2020).

Chemistry of Cr in Soil

The interplay among soil pH, redox potential, and organic matter content creates a complex geochemical environment that governs chromium speciation and transport within the soil (Rasool et al., 2025). Soil pH influences both the speciation of chromium, specifically its oxidation state, and its mobility, particularly its adsorption behavior (Pantsar-Kallio et al., 2001). Chromium changes form depending on the pH of water; Cr(III) precipitates at neutral or basic pH and remains soluble at acidic pH, while Cr(VI) is soluble in water at all pH (Oliveira, 2012). Under acidic conditions, the presence of organic matter and Fe(II) enhances the reduction of Cr(VI) to Cr(III), thereby reducing chromium mobility (Stewart et al., 2003). Alkaline pH conditions, in the presence of low organic matter and manganese oxides, promote the oxidation of Cr(III) to Cr(VI), which consequently increases both the mobility and toxicity of chromium (Ciavatta et al., 2012). Redox potential determines chromium speciation; specifically, reducing conditions favor the conversion of Cr(VI) to Cr(III), whereas oxidizing conditions facilitate the reverse process, the conversion of Cr(III) to Cr(VI) (Kamaludeen et al., 2003).

In anaerobic or oxygen-depleted soil environments, the presence of organic matter and Fe(II) leads to the rapid reduction of Cr(VI) to Cr(III) (Ciavatta et al., 2012). Organic matter plays a dual role regarding chromium, acting simultaneously as a reductant for Cr(VI) and as a complexing agent for Cr(III) (Radziemska et al., 2020). High levels of organic matter in the soil effectively stabilize chromium by completely reducing Cr(VI) to Cr(III), thereby reducing its bioavailability. Conversely, in soils with low organic matter content, the concentration of Cr(VI) tends to be higher due to limited reductive capacity and fluctuations in pH (Chen et al., 2010). Fe(II)-bearing minerals in the soil convert Cr(VI) into less mobile Cr(III), thereby significantly reducing the bioavailability of chromium (Stewart et al., 2003). Manganese oxides can act as oxidants and, under suitable conditions, such as in alkaline environments with low organic matter content, can convert Cr(III) into Cr(VI) (Ciavatta et al., 2012).

Chromium Mobility and Bioavailability

In the environment, Cr(VI) is the most toxic form of chromium because of its mobility and ability to cross membranes in living organisms. Cr(III) is less toxic, and due to its lower solubility and mobility, it is associated with organic matter in soil and water. Cr(III) reacts with Fe at normal water pH to form a hydroxide precipitate. However, Cr(III) reacts with oxygen or manganese oxide to oxidize to Cr(VI) (Oliveira, 2012). The mobility of chromium depends on its oxidation state. Cr(VI) is highly mobile due to its anionic form and high solubility in water, whereas Cr(III) is relatively immobile or less mobile due to precipitation and strong adsorption onto soil particles (Ciavatta et al., 2012). Soil texture, mineral composition, and the presence of competing ions also influence Cr mobility (Caporale and Violante, 2016). The adsorption and co-precipitation of chromium with iron oxides, chromite, and heavy minerals limit its mobility within the soil. Clay minerals and heavy metal minerals serve as reservoirs for chromium, facilitating its release; furthermore, adsorption onto Fe-oxides significantly restricts chromium leaching (Bhattacharya et al., 2020).

The bioavailability of chromium to plants and microorganisms depends on the concentration of chromium in the soil and the capacity of these organisms to take it up (Zulfiqar et al., 2023). Cr(III) is less mobile; consequently, it becomes immobilized within the soil matrix or at plant roots, resulting in minimal translocation to the edible aerial parts of plants. Conversely, Cr(VI), being highly soluble, can leach into groundwater and be absorbed by plants, provided it does not undergo reduction within the soil (Ciavatta et al., 2012). Soil amendments that increase pH, such as limestone and dolomite, reduce the concentration of $CaCl_2$-extractable chromium, thereby decreasing the amount of chromium available to plants (Radziemska et al., 2020). Over time, chromium in the soil transforms into more stable solid-phase forms, which reduces its overall mobility; however, manganese oxides can preserve or even generate Cr(VI). Additionally, changes in redox conditions or contact with saline water can trigger the rapid release of chromium from the soil or perpetuate the persistence of Cr(VI) (Zhao et al., 2026). The concentration and bioavailability of chromium vary across soil particles of different sizes, indicating that soil particle size also influences the bioavailability of chromium (Wang et al., 2025). Soil-dwelling microorganisms enzymatically convert Cr(VI) into Cr(III), thereby reducing the risk of its uptake by plants. Certain endophytic bacteria reduce the bioavailability of chromium by lowering Cr(VI) levels below the detection limit (Kamaludeen et al., 2003). The speciation, properties, and redox reaction of Cr in soil are given in Fig. 2.

Impact of Chromium on Environment and Human Health

Effect on Soil and Water

Chromium pollution degrades the quality of soil and water, thereby profoundly impacting environmental health and the functioning of ecosystems (Xing et al., 2025). Chromium toxicity in the environment depends on its valence state and quantity. Cr(VI) is more dangerous due to its higher mobility, while Cr(III) is less harmful due to its lower mobility (Oliveira, 2012). Due to its high solubility, Cr(VI) present in waste and residual materials not only contaminates the soil but also leaches into the groundwater. In contaminated sites, the release mechanisms of chromium are governed by the presence of chromite, Fe-Cr particles, and a mixture of chromium in various oxidation states (Bhattacharya et al., 2020). Chromium pollution leads to the degradation of agricultural lands and water sources, reducing the availability of clean water and fertile soil essential for crop cultivation (Ertani et al., 2017). The pathways of chromium contamination in soil, surface water, groundwater, sediments, and air can vary depending on the specific sources and prevailing environmental conditions (Ritter, 2002).

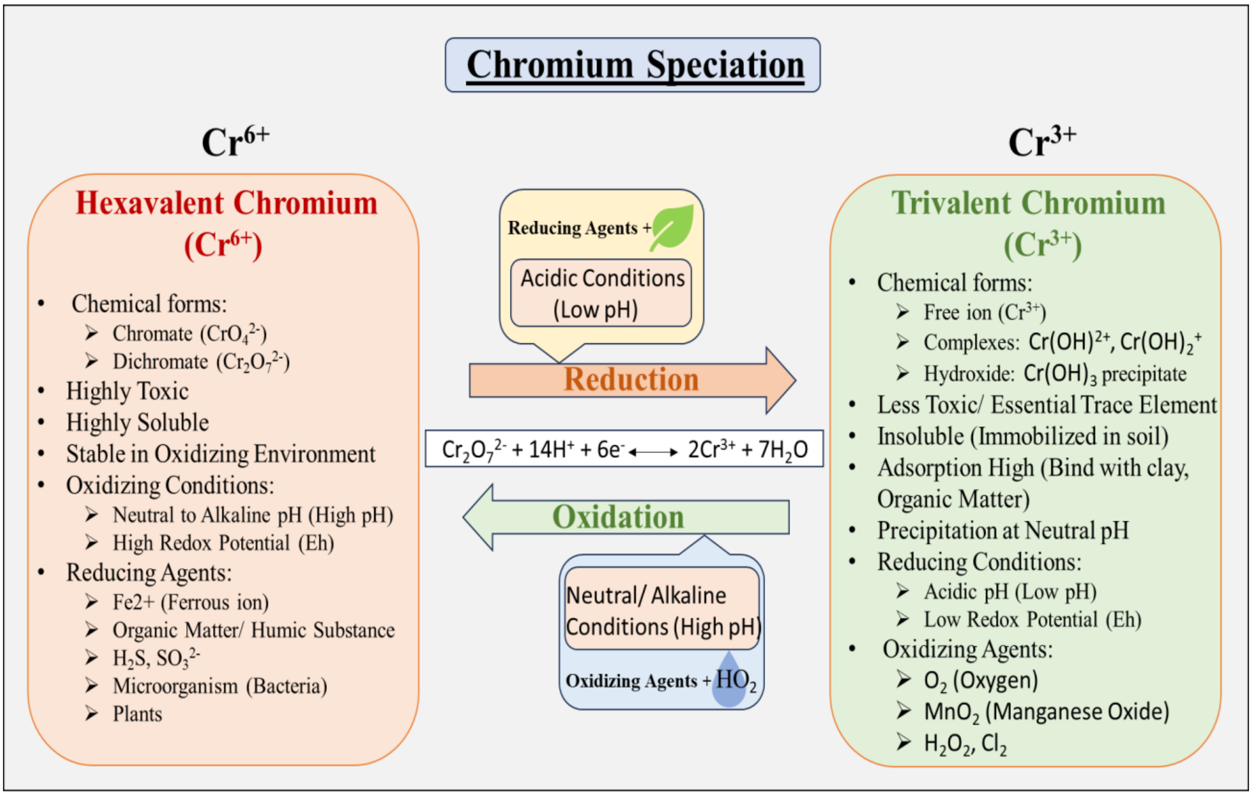

Fig. 2. Chromium: Speciation, properties, and redox reaction.

Elevated levels of chromium in the soil pose a significant health risk to both humans and animals, as Cr-laden dust particles can be inhaled (Junaid et al., 2016). The ingestion of chromium-contaminated soil, particularly by children, in the vicinity of industrial facilities constitutes a major risk factor. The mobility of Cr(VI) and the adsorption of Cr(III) onto mineral surfaces significantly influence the extent and persistence of soil contamination (Stewart et al., 2003). Even in soils with high chromium concentrations, strong adsorption capacities and reduction processes can effectively maintain chromium levels in groundwater below regulatory limits (Bhattacharya et al., 2020). The recommended limit for Cr in water is 1 µg L^{-1} for Cr(VI) and 8 µg L^{-1} for Cr(III). However, Cr values in industrial wastewater can range from 2 to 5 µg L^{-1} (Chandra et al., 1997). However, in areas affected by chromite weathering, high concentrations of manganese oxides, salinity, or specific redox conditions, the risk of prolonged chromium release persists (Trebien et al., 2011). The contamination of groundwater by chromium originating from chromium-bearing waste sources is governed by various processes occurring within the soil, such as dissolution, precipitation, adsorption, and redox transformations (Bhattacharya et al., 2020). The process of sequestering toxic metals in the soil significantly reduces the bioaccessibility of chromium. Organic carbon or Fe(II)-bearing minerals convert Cr(VI) into the less bioaccessible form, Cr(III) (Stewart et al., 2003).

Effect on Human Health

The extensive use of chromium in industries is contaminating soils and water, thereby posing serious threats to humans and ecosystems (Mohanty et al., 2023). The effects of Cr in humans depend largely on its chemical form (Saha et al., 2011). Cr(III) is a micronutrient for humans, used in carbohydrate and lipid metabolism, and is generally harmless. Cr(VI) is toxic to plants, animals, and microorganisms, and is carcinogenic to humans (Genchi et al., 2021). According to numerous reviews and epidemiological data, Cr(VI) is classified as a potent carcinogenic agent in humans, and an increased incidence of lung cancer and other types of cancer has been observed in populations exposed to it (Wang et al., 2017). Since the structure of hexavalent chromate is similar to that of phosphate and sulfate, Cr(VI) enters human and animal cells more readily than Cr(III) via sulfate transporters, reaching various organs and tissues (Costa, 1997). Furthermore, it damages cells by inducing oxidative stress, DNA damage, chromosomal abnormalities, and mutations, thereby promoting the development of cancer (Wang et al., 2017; Hossini et al., 2022). Hexavalent chromium reacts with human cellular components to form Cr(III), causing genotoxicity. The intermediates and reactive oxygen species formed in this process damage the p53 tumor suppressor gene, affecting DNA repair and increasing the risk of mutations and cancer (Das et al., 2021).

Long-term exposure to Cr(VI) is highly toxic and fatal to humans. Excessive exposure to Cr leads to disorders affecting the cardiovascular, respiratory, gastrointestinal, reproductive, and immune systems (Shekhawat et al., 2015; Das et al., 2021; Hossini et al., 2022). Cr(VI) also induces cancers of the stomach, kidney, prostate, lymph nodes (Hodgkin's), genitourinary tract, blood (leukemia), lymphatic system (lymphoma), bladder, and bone in humans and animals (Costa, 1997). In pregnant women, it can cross the placenta to reach the fetus, thereby increasing the risk of developmental disorders, dermatitis, and various cancers (such as lung, stomach, and skin cancer) in both the mother and the child (Shekhawat et al., 2015; Das et al., 2021). Cr(VI) also causes severe non-carcinogenic toxicity (Mohanty et al., 2023; Yan et al., 2023). Non-carcinogenic effects include anemia, asthma, respiratory tract hypersensitivity, epistaxis (nosebleeds), dermatitis (skin inflammation), eczema, skin irritation, skin ulcers, lesions on the skin and mucous membranes, irritation of the eyes and nose, gastrointestinal ulcers, liver and kidney damage, reproductive toxicity, and impairment of immune system function (Monga et al., 2022; Sharma et al., 2022; Mohanty et al., 2023). Chromium affects cellular signalling and neuroprotection, and increases the risk of neurological disorders (Dumpala et al., 2026). Continuous exposure to low levels of Cr causes tissue buildup and has detrimental impacts on health in the workers and surrounding communities (Junaid et al., 2016).

Effect on Plants

Through oxidative stress and metal buildup, chromium pollution is a chronic and hazardous environmental concern that significantly hinders plant development and physiological functioning (Kholiya et al., 2026). Chromium reduces plant length, biomass, and overall growth, and generates ROS, thereby increasing oxidative stress. Chromium stress reduces plant length, biomass, and overall growth, while increasing methylglyoxal (MG) content, protein oxidation, and relative membrane permeability (Yadav et al., 2026). Plants exposed to chromium face a range of issues, including reduced seed germination, stunted growth, and disrupted photosynthesis; consequently, both crop yield and quality decline (Kapoor et al., 2022; Kholiya and Kumar, 2023). Chromium is not essential for plants, but it can have both positive and negative effects depending on its concentration. Low levels of Cr (0.05–1 mg L^{-1}) in plants promote growth and increase yields, while high Cr levels can cause toxicity (Oliveira, 2012; Patra et al., 2024). Plants have no specific mechanism for the absorption of Cr. It is primarily absorbed by the roots through sulfate or phosphate ion transporters. Roots accumulate in higher concentrations than shoots, and plants store Cr in vacuoles to reduce toxicity (Sharma et al., 2020).

Chromium is toxic to plants, and plant health is significantly affected by Cr(VI) toxicity. It impairs plant growth, development, and physiological processes (Shanker et al., 2005). Cr(VI) reduces plant growth parameters such as seed germination, root and shoot growth, leaf growth, and plant yield (Kholiya and Kumar, 2023). It also affects physiological processes such as mineral uptake, photosynthesis, transpiration, protein activity, and electron transport enzyme activity, leading to deficiencies in essential nutrients such as Fe, P, K, and Mg (Das et al., 2021). Cr stress reduces the amount of chlorophyll (Chl a, Chl b, and total chlorophyll) in plants (Kholiya and Kumar, 2023). Cr interferes with the chlorophyll biosynthesis process and inactivates essential enzymes such as δ-aminolevulinic acid dehydratase (ALAD), reducing the rate of photosynthesis, gas exchange, stomatal conductivity, and transpiration (Hassan and Su, 2026). At the biochemical level, Cr stress also affects enzymes such as nitrate reductase and ATPase and induces oxidative stress in plants by generating reactive oxygen species (ROS), including O2– and H2O2, which damage DNA, proteins, lipids, and membranes. Additionally, Cr also affects plant hormonal regulation, altering the concentrations of hormones such as SA, IAA, GA, ABA, and cytokinins (Shanker et al., 2005; Hassan and Su, 2026). Plants employ defense mechanisms to mitigate stress, including enzymatic antioxidant systems (SOD, CAT, POD, GPX, APX), and non-enzymatic antioxidants (glutathione, ascorbic acid, carotenoids, flavonoids, proline, etc.), which neutralize ROS and protect cells (Hassan and Su, 2026). However, at high Cr levels, the effectiveness of these protective systems is blocked, leading to significant metabolic damage, reduced plant productivity, and eventual plant death (Shanker et al., 2005). The responses of plants to Cr toxicity are summarized in Fig. 1.

Impact on Ecosystems and Food Chains

Chromium contamination as a persistent inorganic heavy metal pollutant degrades soil fertility and ecosystem quality (Kumar, 2020). Chromium also harms the natural environment through food chains and transportation (Fishbein, 1981). Elevated levels of Cr(VI) disrupt biodiversity and environmental balance by altering the growth, structure, and physiology of microorganisms such as bacteria and algae (Das et al., 2021). Hexavalent chromium causes significant harm to humans, as well as to soil, water, plants, animals, and the broader ecosystem. Due to its mobility and persistence, Cr undergoes bioaccumulation through food chains, thereby adversely affecting the health of organisms. Cr(VI) present in soil and water acts as a highly ecotoxic element, as it causes damage to microorganisms, plants, animals, and aquatic life (Xia et al., 2019; Murthy et al., 2022).

Chromium accumulated in plants from contaminated soil enters the food chain, eventually reaching animals and humans, even those situated far removed from the sources of pollution, thereby escalating health-related risks (Kapoor et al., 2022; Edo et al., 2024). Chromium pollution poses a threat to human livelihoods and the ecosystem services provided by natural systems, as it leads to soil degradation, water contamination, and negative impacts on biodiversity within the polluted ecosystems surrounding chromite mines and leather tanneries (Hossini et al., 2022; Mortada et al., 2023). Effective monitoring, regulation, and remediation measures are essential to safeguard human health and the integrity of the environment.

Conclusion

Chromium enters the environment through both natural and anthropogenic activities and is primarily found in the forms of Cr(III) and Cr(VI). Compared to Cr(III), Cr(VI) is highly soluble, mobile, and bioavailable. Chromium speciation determines the transport, bioaccumulation, and toxicity of chromium within plants, animals, humans, and the entire ecosystem. Cr enters plants through sulphate or phosphate transporters and primarily accumulates in roots, it can nonetheless translocate to other parts of the plant, inducing toxicity that leads to a decline in crop yield and quality. In animals and humans, exposure to and bioaccumulation of Cr(VI) result in adverse health effects, including respiratory and gastrointestinal damage, reduced fertility, impaired liver and kidney function, anaemia, dermatological disorders, and various types of cancer. In aquatic systems, the cycling of chromium is highly complex and can also lead to biomagnification. As chromium poses a threat to both the environment and living organisms, preventing its entry into and dispersion within the environment is of great importance. To this end, the large-scale application of cost-effective and highly efficient techniques such as bioremediation and phytoremediation can prove to be effective remedies.

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