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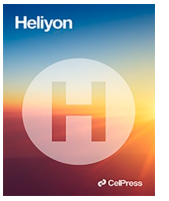

Review article

Human exposure to chromite mining pollution, the toxicity mechanism and health impact

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ABSTRACT

Significant amounts of toxic metal-containing mining waste are produced by chromium mining activities, along with the production of air pollutants. The presence of toxic metals in various environmental media including air, water, and soil, along with their chemical species such as hexavalent chromium, pose major health hazards for both directly exposed mining workers and the population residing near the mining areas. Highlighting the requirements for enhanced environmental protection and safety measures, this comprehensive review shed light on the global environmental pollution stemming from chromite mining activities. Based on the published literature, the study also investigated into the pollution caused by toxic metals and explored their probable health effects on exposed individuals. The exposure routes and the mechanisms of toxic metal induced carcinogenicity in the exposed groups were assessed. Additionally, the generated reactive species in exposed individuals and the toxicity mechanisms of hexavalent chromium were discussed. Considering these findings, this review proposed the necessity of cross-sectional biomonitoring studies involving occupationally exposed workers from chromite mining operations. The anticipated impact of this review is to influence the global and national chromite mining industry, instigating improvements in occupational settings, real-time pollution monitoring, and healthcare provisions for exposed workers.

1. Introduction

Ore mining and smelting along with the related industrials activities act as the main sources of toxic metals in various environmental media [1,2]. Mining involves extracting and utilizing metallic and nonmetallic minerals found in mineral and ore deposits. It is one of the most important industries for any country where coal, copper, gold, chromite, and other important metalliferous deposits are discovered, extracted and utilized [3]. Despite its high economic value, mining is considered a significantly hazardous occupation due to the frequent occurrence of severe mining injuries, health complaints, and fatalities [4]. Regions with extensive industrial activities covering mining, smelting, and other metal-based manufacturing processes are usually tagged as being highly polluted [5]. Globally, mining is one of the largest industries with millions of employees associated, who are involved in different kinds of jobs such

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as ore extraction, loading, machine operation, maintenance, etc. [6,7]. The employees engaged in mining and the related industrial activities, as well as the nearby residents, are highly exposed to toxic metals [8,9]. Several studies have reported elevated level of toxic metal pollution and high health risks for the workers exposed to and people living around the mining sites [9,10].

Chromite ore mining is a typical mining industry with substantial environmental hazards. Chromium metal derived from industrial chromite mining is used in the production of stainless steel, leather industry, paint industry, and other important industrial usages [11]. Nevertheless, the presence of chromium ions, particularly hexavalent chromium (Cr(VI)) in soil, groundwater, and surface water poses serious threats to public health [12]. Prolonged exposure to Cr(VI) has been connected to a variety of adverse health effects, including abdominal disturbances, gastrointestinal issues, weakened immunity, and the development of conditions such as stomach cancer, diarrhea, tumors, and ulcers [13]. Due to its high toxicity and cancer-causing properties, the International Agency for Research on Cancer (IARC) has declared Cr(VI) as Group 1 human carcinogen [14].

The largest countries in terms of chromite production are South Africa, Kazakhstan, India, Finland, Türkiye and Pakistan. Over the last few decades, the mining industry in Muslimbagh in Pakistan and Jharkhand in India has developed at a rapid pace. From ore extraction to processing for quality improvement, open dumping of mining wastes into surrounding areas has severely contaminated air, water and agricultural field soil with hazardous metals, causing serious health issues. Besides, mining workers typically operate for extended periods without the adoption of rest, break, and job rotation policies [8]. Human biomonitoring studies are essential to assess pollutant exposure and its health effects, particularly for workers exposed to heavy metals like chromium. While there are tangible studies conducted in top chromite producing countries to evaluate the environmental contamination and health risks stemming from those mining activities, a systematic review of the pollution status, environmental hazards, and the related toxicity mechanism of chromite mining is essential to promote the complete enforcement of occupational safety and health practices for labor in mining activities in developing countries.

This review highlighted the environmental pollution resulted from the chromite mining and processing industries globally, examined the probable toxicity mechanisms of the related toxic metals on exposed workers as well as other human population, and summarized the cross-sectional biomonitoring studies involving chromite mining workers. With a particular focus on the health risks of Cr(VI), this study aims to drive improvements in global occupational safety, pollution monitoring, and healthcare provision of chromite ore mining.

2. Methodology

To evaluate the effects of hazardous metal contamination from chromite mining, a comprehensive review was carried out, with particular attention to human exposure, chromium toxicity mechanisms, and biomonitoring investigations. Using keywords including chromite mining pollution, mining occupational hazards, and chromium toxicity across databases including PubMed, Scopus, Web of Science, and Google Scholar, the review adhered to an organized process, as illustrated in Fig. 1. After the search was narrowed down using Boolean operators (AND, OR), 346 pertinent journal articles were found. Only peer-reviewed journal papers were included while conference abstracts and non-peer reviewed papers were not included. 156 papers were chosen for the review using a phased screening procedure that eliminated about 190 publications based on the content of the title and abstract.

The quality of the chosen studies was assessed based on the following criteria: robustness of the data analysis, measurement

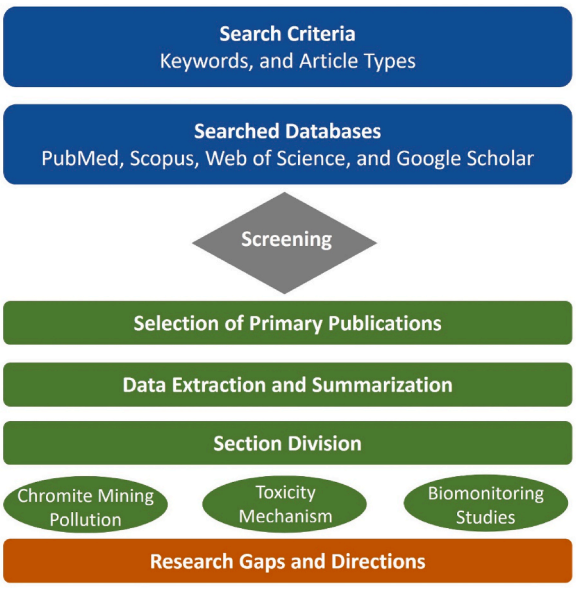

Fig. 1. Framework of review methodology utilized in this study.

techniques, sample size, and study design. Data on study titles, authors, publication year, study site, sample collection and analysis techniques, major conclusions about the health effects of toxic metal exposure, outcomes of biomonitoring, and hypothesized mechanisms of chromium toxicity were retrieved. Tables 1–3 provide a summary and presentation of the results. The three primary aspects of the review were biomonitoring initiatives, toxicity mechanisms of chromium, and pollution and human exposure from chromite mining. To find similar themes on contamination levels, health hazards from occupational exposure, and the application of biomonitoring, a comparative analysis was carried out. This thorough analysis gives recommendations for better risk management and mitigation techniques in addition to insights into toxic metal contamination from chromite mining.

3. Results and discussion

The detailed full text evaluation of selected publications on chromite mining pollution revealed key trends in global chromite mining pollution studies. This section presents data and techniques related to exposure to toxic metals, chromium toxicity mechanism, and biomonitoring studies for exposure assessment. Data from 12 studies ranging from 2006 to 2022 on toxic metal concentrations in dust and soil are presented in Table 1. Concentrations of toxic metals such as Chromium (Cr) Nickel (Ni), Lead (Pb), Cadmium (Cd), Manganese (Mn), Zinck (Zn), and Iron (Fe) are calculated in soil and dust samples form mining areas with a majority from chromite mines. Chromium concentrations are reported ranging from 138 mg kg^{-1} in Spain [20] to 32,063.4 mg kg^{-1} in India [15]. Dust samples show chromium levels from 420 mg kg^{-1} in Pakistan [48] to 7070 mg kg^{-1} in South Africa [24]. The studies highlight significant environmental impacts of chromite mining across regions like India, Pakistan, Vietnam, and South Africa. Furthermore, Table 2 outlines different exposure routes such as inhalation, ingestion and dermal contact for miners, industrial workers, farmers, and nearby residents. The studies mentioned used biological samples such as blood, urine, hair and nails to assess short-term and long-term exposures to toxic metals like lead, chromium, cadmium, and mercury. Similarly, Table 3 compiles 19 biomonitoring studies from 1999 to 2024 taken from the selected publications on urinary heavy metals. These studies have assessed levels of urinary heavy metals of exposed subjects in different occupational settings with chromium values ranging from 0.95 μg/g creatinine in occupationally exposed iron and steel workers [44] to 58.15 μg/g creatinine in surgical industry workers [41]. Apart from Chromium, the concentrations of other toxic metals such as urinary Cadmium (Cd), Nickel (Ni), Copper (Cu), Manganese (Mn), Zinc (Zn) and Lead (Pb) are also listed. These results collectively provide a comprehensive view of toxic metal exposure and health risks in occupational settings globally.

3.1. Global chromite mining and processing

Chromium can appear in 82 diverse ore types, but chromite is the sole type extracted in significant commercial quantities and serves as an essential raw material in the stainless steel manufacturing process [49]. Chromite ($FeCr_2O_4$) is a naturally occurring mineral that falls under the spinel group of minerals. Chromite ore occurs exclusively in ultramafic igneous rocks and its general formula can be expressed by $(Mg_xFe_{1-x})\ O{\cdot}(Al_yCr_{1-y})_2O_3$ [22]. There are two forms of commercial chromite deposits found in the world, including irregular podiform and stratiform seam deposits. The major global reserves of chromite are found in South Africa, followed by countries in Asia and Europe, as well as Australia and Brazil [12]. There are over 12 billion tons of chromite of shipping grade available worldwide, which is enough to supply all potential demand for several centuries. A majority of the chromium resources in the world (95 %) are concentrated in South Africa and Kazakhstan. The probable exploitable deposits in India are 100 million metric tons and fairly large deposits are also found in Pakistan [50,51]. In 2021, the global production of chromite amounted to 410 metric million tons, with South Africa contributing the highest share at 18 million metric tons.

The specific hazards in chromite mines are based on factors such as mine type and depth, chemical composition of mineral and ore, and the techniques employed for extraction, transportation and processing. The generated dust containing different toxic elements is dispersed by wind, vehicular traffic and other machinery employed in the working areas [10]. Chromite mining in specific may contribute highly to pollution as comparatively it is hard mineral ore and is mined by dynamite blasting prior to extraction, transport, and further processing. Moreover, dry milling is identified as the sole process for ore beneficiation, and is highly associated with the production of toxic hexavalent chromium [52,53].

Stainless steel production is the primary application of chromium, as chromium is an important element for producing ferrochrome alloys and special type steel [50,54]. Around 90 % of mined chromite ore undergoes transformation within the metallurgical industry, resulting in various grades of ferrochrome [50]. About 80 % of the ferrochrome produced is consumed by stainless steel [55]. Chromite ore is processed prior to marketing or export, and the intended treatment depends on the ore primary source, parent rock material and planned end use. Chromite often shows variations in its composition (Mg, Cr, Al, Fe^{2+}, Fe^{3+}) and is generally divided into three different class types based on their usages and grades. In the metallurgical grade, this ore contains 44–56 % Cr_2O_3 and the Cr/Fe ratio is around 2:5. The second type is the chemical grade, characterized by substantial iron content with a Cr/Fe ratio approaching 1. And the refractory grade is at the third place, which contains comparatively great amounts of Al_2O_3 usually greater than 20 % [56,57]. Simple mechanical sorting and washing are often sufficient for upgrading the extracted ores from the mine. However, for international marketability, all low-grade and finely dispersed ores require upgrading through various separation and concentration techniques, such as flotation, gravity concentration, selective flocculation, electrostatic separation, and magnetic separation, which usually cause severe environmental hazards in the local and occupational settings [53,54].

Table 1
Concentration/range of toxic metals in dust and soil samples from major mining areas worldwide (mg kg^{-1}).

Study area	Mining type	Sample	Cr	Ni	Pb	Cd	Mn	Zn	Fe	References
Pakistan	Chromite mine	Dust	420.0	38.76	7.94	5.08	46.8	–	–	[8]
India	Chromite mine	Soil	14749.22–32063.4	5460.4–8865.9	70–208.5	0.95–5.25	209–360	221.2–349.32	531.8–28847	[15]
India	Chromite mine	Soil	404–49100	45–3688	0–67	–	284–5553	42–131	–	[16]
Pakistan	Chromite mine	Soil	202–564	58–270	8.0–58	1.0–5.0	–	17–43	–	[17]
Iran	Chromite mine	Soil	156.19	321.7	–	–	–	–		[18]
India	Chromite mine	Soil	2622–27963	–	–	–	–	53.1–133.5	–	[19]
Spain	Copper mine	Soil	138	121	24.7	–	–	176	–	[20]
India	Chromite mine	Soil	1715.8–9548.5	223.8–522.8	–	–	1052.3–1993.6	10.9–24.0	21823.7–58490.1	[21]
China	Gold mine	Soil	302.64	–	271.31	1.3	–	142.34	–	[22]
Vietnam	Chromite mine	Soil	5750	5590	–	–	–	–	–	[23]
South Africa	Ferrochrome production	Dust	7070	–	–	–	–	–	–	[24]
Spain	Silver and lead mines	Soil	–	–	8300	40.9	–	12500	–	[25]

Table 2
Exposure routes and analysis of biological samples as biomarkers in assessing toxic metal exposure.

Study area	Subject	Exposure route	Sample	Analysis subject	Reference
Iraq	Smokers	Smoking: inhalation	Urine	Cr, Cd, Pb	[26]
Pakistan	Chromite mining workers	Air: dermal contact, inhalation and ingestion	Blood & Urine	Cr, Cd, Pb, Mn, Zn	[8]
Thailand	Electronic waste workers	Air: dermal contact, inhalation and ingestion	Blood & Urine	Cd, Mn, Pb	[27]
Pakistan	Lather tanning workers	Air: dermal contact, inhalation and ingestion	Urine	Cr, Cd, Ni, Cu, Zn, Pb	[28]
Nigeria	E-waste workers	Air: dermal contact, inhalation and ingestion	Blood	Blood malondialdehyde, Catalase, Superoxide Dismutase and Glutathione Peroxide	[29]
Pakistan	Adult and children	Air and food: dust exposure, drinking water and food.	Toenail	Cr, Mn, Co, Ni, Cu, Zn, Cd, Pb.	[30]
Qatar	Immigrant Farm workers	Air, food intake: inhalation and ingestion	Toenail	As, Ba, Cd, Cu, Mn, Mo, Pb, Se,	[31]
United States	Welders	Air: inhalation	Toenail	Pb, Mn, Cd, Ni, As	[32]
China	E-Waste employees	Air: dermal contact, inhalation and ingestion	Blood	Pb, Cd, Cr, Ni	[33]
France	Welders	Air: dermal contact, inhalation and ingestion	Blood	DNA gene polymorphisms (GSTM1, GSTT1)	[34]
Italy	Cr plating workers	Air: dermal contact, inhalation and ingestion	Urine	Cr	[35]
Germany	Incinerator	Air: dermal contact, inhalation and ingestion	Urine	Cd, Ni	[36]

Table 3
Levels of urinary heavy metals of the exposed subjects in different occupational settings.

Study area	Exposed group	Cr	Cd	Ni	Cu	Mn	Zn	Pb	Reference
Iraq	Smokers[c]	1.93	1.18	–	–	–	–	0.07	[26]
United States	Cardiovascular disease patients[a]	–	0.24	–	–	–	–	0.48	[37]
China	Suburban population[a]	–	1.05	2.25	–	–	–	0.96	[38]
Germany	Non-specifically exposed[a]	–	0.16	1.40	–	–	–	0.59	[39]
Malaysia	Malaysian adults[a]	–	0.35	4.49	–	–	–	0.70	[40]
Thailand	Electronic waste workers[b]	–	0.65	–	–	7.07	–	6.58	[27]
Pakistan	Leather manufacturing workers[a]	5.16	2.9	0.93	2.31	3.39	18.12	7.58	[28]
Pakistan	Surgical industry workers[a]	58.15	41.38	12.04	2.53	5.57	215	10.15	[41]
Pakistan	Working children[a]	0.38	0.36	3.33	11.5	1.5	169	3.6	[42]
Pakistan	Surgical industry workers[a]	23	0.48	7.45	16.3	3.33	278	4.27	[43]
Spain	Iron and steel workers[a]	0.95	0.25	1.67	–	0.93	–	22.28	[44]
Poland	Slide bearings workers[a]	-	–	–	17.8	–	334	25.5	[45]
Pakistan	Steel mill workers[a]	18.58	15.41	9.479	–	–	–	147.48	[46]
Italy	Chrome plating workers[a]	7.31	–	–	–	–	–	–	[35]
Germany	Incinerator workers[a]	-	0.45	14.8	–	–	–	–	[36]
Germany	Dry cell workers[a]	-	-	–	–	0.26	–	–	[47]

[a] unit in μg L^{-1}.
[b] unit in μg g(creatinine)$^{-1}$.
[c] unit in mg L^{-1}.

3.2. Exposure to toxic metals in chromite mining environment

3.2.1. Chromium and other metals in chromite mining

Mine tailings, wastes from smelters, and metals deposited from atmosphere are the primary sources of metal contamination in soil [58]. It has been noted that in the vicinity of smelting practices and mining zones, metals typically coexist as a mixture. For example, Pb and As were frequently found to coexist in the air, soil, and domestic dust around the smelters and mining areas in Mexico [59]. Similarly, the soil and plants in Mahd Ad-Dahab, a city of Saudi Arabia's Hejazi region, were significantly contaminated with more than thirteen toxic metals from nearby mining activities [60]. In the chromite mining areas of Karnataka, India, several heavy metals were also found to be high in concentration in soil, and the heavy metal enrichment in soil was attributed to the five mining sites in this area [61].

High concentrations of metal pollutants are always anticipated in the chromite mining environment. As shown in Table 1 and Fig. 2, high concentrations of Cr, Pb, Cd, and several other heavy metals have been previously found in smelters and mining areas in various countries, with levels many folds higher than the concentrations found in control or far from the pollution source. Waste rock, tailings and slag that are waste materials generated by mining activities in large amounts can in turn lead to environment contamination ultimately [62]. Metals in high concentration are reported in food crops, agrarian soils and streams as a direct outcome of release and

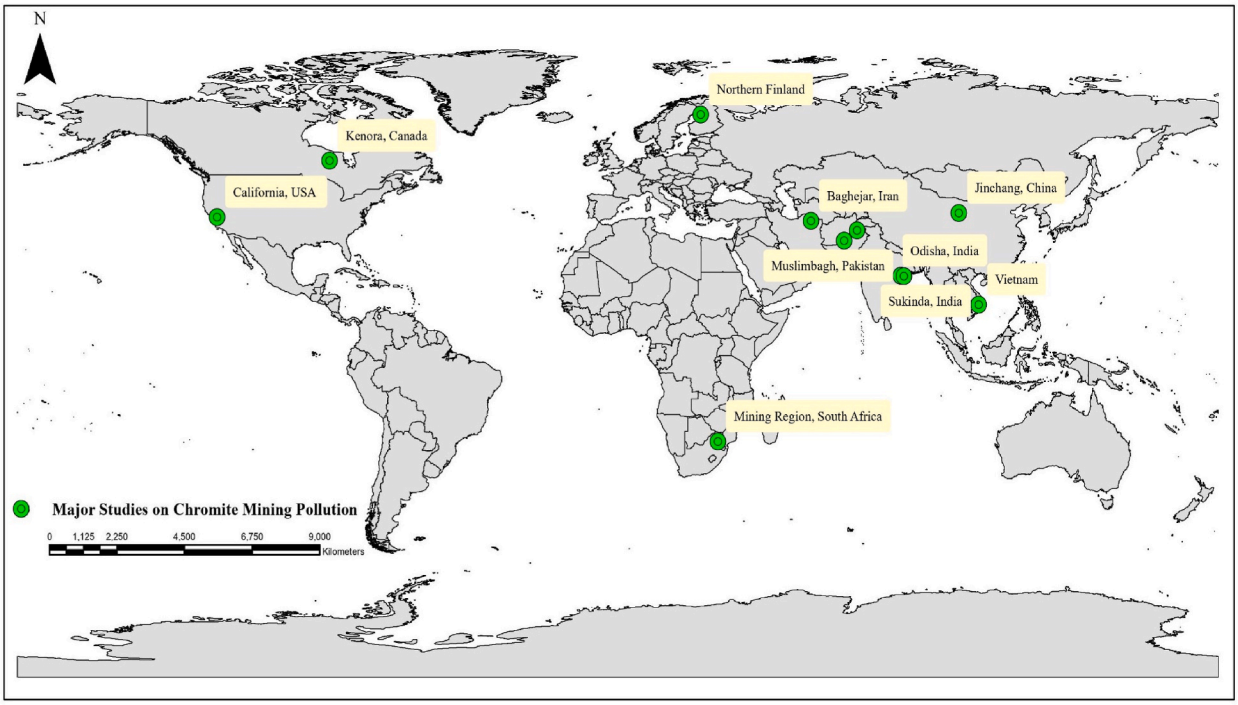

Fig. 2. Major study areas on chromite mining pollution worldwide.

dispersion of mining effluents [63]. [64] reported the application of a passive bio-indicator, Scots pine (Pinus sylvestris L.) bark, in heavy metal monitoring and found that the regular concentration of heavy metals in pine bark in the open-pit chromite mine area (Kemi–Tornio) of northern Finland exceeded the background concentration. Besides, a significant amount of fine particles are generated and dispersed over extensive distance from the source during specific mining processes, which would contaminate the environment through wet and/or dry atmospheric deposition [64]. In Vietnam, some chromite mining operations at small scale were related to high contamination of nearby agricultural soil with Cr, Co and Ni after heavy rains distorted a soil barrier [23].

3.2.2. Human exposure to chromium

Mining activities lead to the pollution of water, soil, and air through heavy metal accumulation and also result in contamination of the surrounding area through diverse processes [21,19]. A chromite mining study in Pakistan revealed that in the impact areas of chromite mining, the toxic metal concentration including Cr, Pb, Cd, and Ni in drinking water exceeded the permissible limits [65]. The Cr(VI) pollution in both surface and ground waters as direct consequences of chromite mining activities have also been revealed in India [54]. In USA, (Cr(VI)) naturally occurs in groundwater in parts of California, Arizona, and San Francisco, primarily due to the hydrolysis of feldspar, Cr-bearing pyroxenes, chromite, and calcite [54]. Chromium pollution in Southwest, Northwest, and North China primarily stems from mining activities, particularly those involving chromite deposits. Cities like Jinchang and Panzhihua are notably affected [66]. In India, a 2007 “Black Smith Institute Report” advised that residents within 1 km from the chromite mining site were significantly associated with diseases that were brought by pollution specifically due to Cr(VI) [67].

Generally, humans are exposed to harmful elements such as hazardous metals by means of three major routes, which are dermal contact, ingestion, and inhalation, as summarized in Table 2. Previous studies indicate that the inhalation of ionic species of toxic metals such as Cr, Pb, and Cd is the primary route contributing to health risks associated with these exposures. Once inside the human body, there is strong adsorption, accumulation, and biomagnification of toxic metals, leading to a wide variety of diseases [68]. For example, prolonged exposure to dust from chromite mines in occupational settings can cause various autoimmune diseases and high risk of lung cancer [69].

Chromium exists in the more common trivalent chromium Cr(III) form, but the industrial significance of the hexavalent chromium (Cr(VI)) form, found in chromate compounds, is notable. Chromite mining ores serve as a major source of chromium production. Other occupational exposures to chromium typically occur in the production of stainless-steel as well as chrome plating and tanning industries. While nasal mucosa irritation and considerable sneezing can be caused by breathing in Cr(VI) with a concentration of 2 $\mu g\ m^3$, the Cr(VI) concentration in air can get much higher in occupational settings depending on the types of processes carried out [70,71]. Therefore, chromium compounds often show acute adverse effects as a result of occupational exposures.

As discussed earlier, Cr(VI) is recognized to be carcinogenic whereas the toxic dose varies depending on the exposure route. Long-term exposure results in bioaccumulation in tissues, which affects the immune system, liver, and kidney [72]. Acute exposure above 5 mg kg^{-1} day^{-1} may cause severe gastrointestinal, renal, and liver damage. For a lifetime of exposure, the EPA’s oral reference dose

(RfD) of 0.003 mg kg^{-1} day^{-1} is considered safe. However, the lung cancer risk can rise even at 1 μg m^{-3} for Cr(VI) inhalation [73]. According to the European Union Scientific Committee on Occupational Exposure Limits (SCOEL), 40 years of exposure to 1 μg m^{-3} of Cr (VI) could lead to four more instances of lung cancer per 1000 workers [74]. In Europe, the current binding occupational exposure limit for Cr (VI) is 10 μg m^{-3} (8-h time weighted average), which will be reduced to 5 μg m^{-3} by 2025. In France and the Netherlands, the occupational exposure limit is much stringent, at 1 μg m^{-3} [75].

3.3. Chromium toxicity and the potential mechanisms

3.3.1. General impacts on human body

It has been recognized that there is a significant association between toxic metals, chemical toxicants, and a high risk of human cancer [76]. Severe heavy metal pollution from the mining areas also highlighted the elevated health risks for the exposed group, including both carcinogenic and non-carcinogenic risks [77]. [78] reported 'high' cancer risk in mining sites for both adults (5.38E-04) and children (4.45E-04). In contrast, other study sites of agricultural and roadside soils exhibited cancer risk ranging from 'low' to 'very low'. This was attributed to the significant contributions of metals including Ni, Pb, and Cr(VI) (73 %, 11 %, and 10 %, respectively).

Chromium has been evidenced as a lethal, cancer-causing and mutagenic metal posing serious threat to the exposed group. There are two stable forms of chromium present in the environment, which are trivalent (Cr(III)) and hexavalent (Cr(VI)) chromium. Cr(III) is recognized as insoluble and less toxic, while Cr(VI) is highly soluble and extremely toxic, known as a carcinogen [70,79]. Human and animal-based studies recognized the importance of trace quantities of Cr(III) (50–200 μg day^{-1}) as essential in maintaining normal glucose metabolism [80]. Cr(VI) is usually more readily absorbed than Cr(III), but the absorption rate relies on the compound type. The fatal oral dose is estimated to be 50–70 mg chromates per kilogram of body weight for adult humans [80,81]. The toxic doses of chromium by oral ingestion mainly take effects through liver and kidney necrosis.

The most common adverse effects after a prolonged exposure of Cr(VI) usually include abdominal disturbance, gastrointestinal and stomach cancer, weak immunity, diarrhea, tumor, and ulcer [82–84]. The assessment by IARC based on different studies indicated a

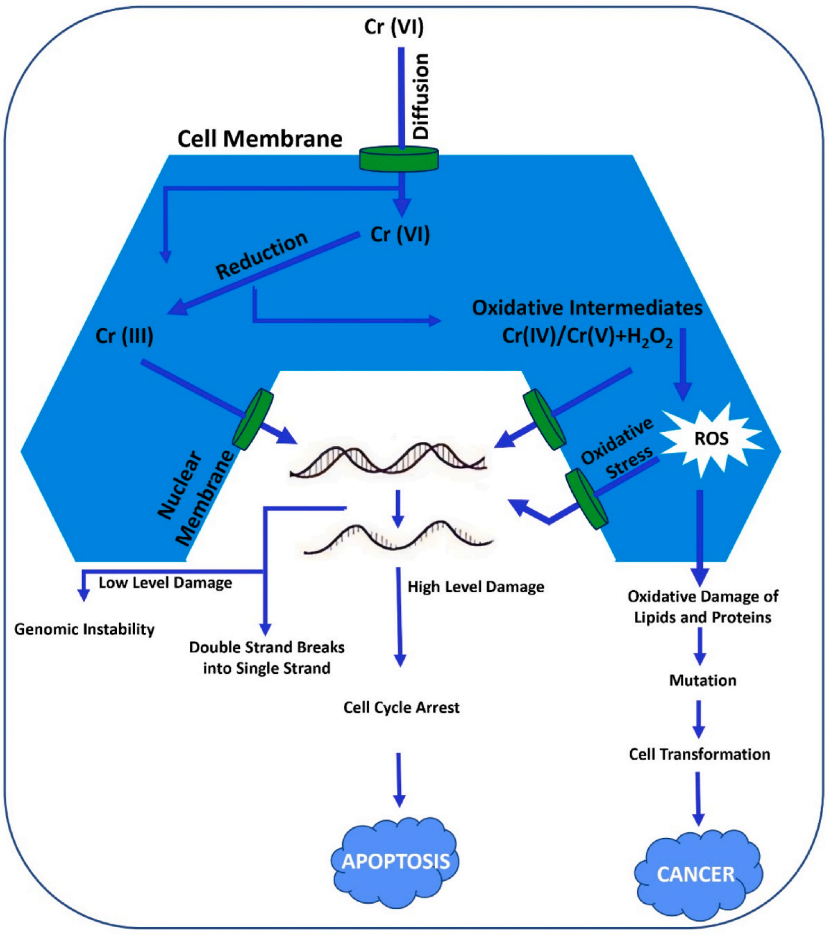

Fig. 3. Intracellular toxicity and carcinogenicity of Cr(VI): potential mechanisms leading to cell cycle arrest [10,95].

lung cancer risk in workers who are exposed to Cr(VI) through inhalation, especially those in electroplating and chromate and/or chromate pigment manufacturing industries [84,85]. Inhalation of hexavalent chromium Cr(VI) compounds results in marked irritation in the respiratory tract and bronchial asthma in human body. The rip of the nasal septum and ulceration have arisen regularly in workers who work in the chromate related industries. Bronchospasm pneumonia and rhinitis have also been reported in workers who were exposed to Cr(VI) together with respiratory dynamics impairment during respiration [86]. Moreover, workers exposed to chromium-containing materials consistently report acute irritative dermatitis and chronic skin ulcers. Ulceration as a result of interaction with through damaged skin and mucous membrane is also a common occupational damage when suitable workplace protection is absent [87]. The powerful oxidizing and strong acidic properties of soluble Cr(VI) have been recognized as the main reasons of its irritant effect on epithelia [88].

3.3.2. Chromium genotoxicity and carcinogenicity

The uptake of chromium in human body is mainly through the gastrointestinal tract, lung, and to a lesser extent, the skin via dermal contact [10]. Chromium excretes through the body whereas kidney/urine and bile/feces are the key routes for the elimination of chromium [89]. Upon exposure to Cr(VI), this chemical specie enters the cell more easily than Cr(III) compounds and is eventually reduced to Cr(III). The Cr(VI) reduction is considered a detoxification process in the body if this reduction occurs away from the actual target site. However, if the reduction occurs inside or around the cell nucleus of the target, it may activate the chromium toxicity in organs [84]. It is recognized that the intracellular reduction of Cr(VI) infers the formation of short-lived chromium species in pentavalent chromium form with strong attraction for cellular constituents [90]. The early binding of cellular macromolecules might involve the pentavalent chromium. The key factors for the intracellular reduction of Cr(VI) appear to be glutathione and cysteine, which can stabilize pentavalent chromium [91]. When the chromium species are eventually absorbed and retained in the biological tissues of the body, the chromium compounds predominantly exist as Cr(III).

Prolonged exposure and high doses of chromium can result in various genotoxic and cytotoxic reactions which can then impact the whole-body system. However, on the other hand, the Cr(VI) induced cytotoxicity mechanism is still not fully understood. As shown in Fig. 3, the reduction process through which Cr(VI) is converted to Cr(III) can give rise to various kinds of DNA damage, including chromium-DNA adducts, DNA-protein cross-links, DNA-DNA inter-strand crosslinks, as well as other oxidative DNA lesions such as strand breaking. In a series of in vivo and in vitro studies, it has also been demonstrated that Cr(VI) tends to trigger oxidative stress through the elevation of reactive oxygen species (ROS). This, in turn, ultimately results in oxidative degradation of proteins and lipids and genomic DNA damage [10,92]. Due to the elevated oxidative stress imposed by Cr(VI), a cascade of cellular events ensues, including the high production of ROS such as hydroxyl radicals and superoxide anions, genomic DNA fragmentation, increased lipid peroxidation, protein kinase C activation, intracellular oxidized state modulation, altered gene expression, and apoptotic cell death [93,94].

Inflammation plays a key role in Cr(VI)-induced illnesses. Previous studies have shown lung inflammation and signaling pathway activation in animals, along with increased interleukin–6 (IL-6) in Cr(VI) exposed workers [96,97]. Alveolar macrophages convert Cr (VI) to a less harmful form but also produce pro-inflammatory cytokines and reactive oxygen species, potentially leading to lung damage and fibrosis [87]. Exposure to Cr(VI) stimulates macrophages, which in turn releases inflammatory mediators such as IL-1beta, IL-23, and IFN-gamma. This systemic inflammation raises the risk of lung illnesses, destroys lung tissue, and reduces lung function. In the study by Zhang et al., higher blood levels of pro-inflammatory cytokines and the inflammatory biomarker suPAR, which is connected to chronic lung illness, were found to correlate with higher blood chromium levels [96].

3.3.3. ROS generation and the induced oxidative stress

The genotoxic effects of toxic metals are multifactorial, involving direct interference with enzyme activity, deactivation of antioxidant sulfhydryl pools, as well as competitive inhibition of the absorption of essential trace minerals [98,99]. It has been previously reported that healthy individuals living in and around the severely polluted mining area with heavy metal contamination can experience substantial changes in the expression of DNA repair genes and detoxifying genes as well as some xenobiotic metabolizing enzymes [100]. Several studies have acknowledged that exposure to elements like Cd and Pb is associated with obviously increased lipid peroxide levels and altered antioxidant enzyme activity [101,102]. According to a study by Ref. [29], the markedly elevated blood malondialdehyde (MDA) concentration in the study group exposed to e-waste could directly indicate the enhanced lipid peroxidation and thus the elevated oxidative damage, which is an important mechanism contributing to carcinogenesis.

Heavy metals such as Cr, Pb, Cd, and As can exert similar cellular impact by increasing oxidative stress [103]. Oxidative stress is in fact an imbalance between the levels of pro-oxidants producing ROS and antioxidants within the human body [104]. Exposure to heavy metals can lead to the generation of a fatal amount of ROS during the metabolism of toxic heavy metals within the body. This, in turn, causes oxidative damage to different human organs [105,106]. Typically, oxidative damage involves the proliferation of ROS, which subsequently alters the molecular structure of nucleic acids, lipids, and proteins through detrimental interactions. Blood malondialdehyde (MDA), a product of the lipid peroxyl radical breakdown in cells, is a singular lipid peroxidation product. Its concentrations can be used to indicate the level of lipid peroxidation in human body [107]. In a study by Yiin et al., the lipid peroxidation assessment through MDA analysis revealed an increase in lipid peroxidation in the presence of Pb [107]. Additionally, the MDA concentration also showed an increase in the liver and kidney upon exposure to Cd. Other studies have also consistently reported lipid peroxidation as a consequence of heavy metal toxicity [29,102].

ROS induction in the body by metals are termed cytotoxic properties of metals that ultimately results in DNA damage. The potential pathway for the induction of oxidative damage in cells treated by metal may involve the iron release from ferritin and the subsequent formation of ROS, which is highly dependent on iron [108,109]. Another potential pathway may involve the activation of NADH

oxidase and the production of super oxides, as described by Lynn et al. [110]. The Fenton reaction facilitated by copper is also an important process, which catalyzes the formation of hydroxyl radicals [59]. On the other hand, antioxidant enzymes, including glutathione reductase (GR), superoxide dismutase (SOD), and catalase (CAT), are of vital importance in individual adaptive response to toxic metal exposure. Antioxidant can eliminate major ROS such as super oxides and peroxides, preventing the production of additional harmful species near cells or DNA. However, an imbalance between oxidants and antioxidants can lead to oxidative stress, as characterized by an increased generation of ROS, which may overwhelm the cell's central antioxidant defence system [111,112].

3.4. Exposure assessment of heavy metals by human biomonitoring

Human biomonitoring (HBM) is a method employed to assess pollutant exposure by monitoring environmental chemicals and the reaction products in biological samples such as hair, urine, milk, and blood [113–115]. As a rapidly developing discipline, HBM is often applied to assess pollutant exposures and risks regarding environmental and occupational health, contributing not only to scientific understanding but also influencing the development and implementation of programs and policies aimed at protecting human health [116]. Various toxic heavy metals, gases, and dust fumes are present in different occupational settings, particularly in industries where metals are widely used for various manufacturing processes. It is acknowledged that metals and the related compounds can pose toxic effects when their concentrations go beyond established limits [117]. Typically conducted in cross-sectional studies, the objective of biomonitoring is to gauge human exposure by comparison of toxic element concentrations in the exposed group with those of unexposed individuals for control, or with 'background' values based on literature results [116,118]. The quantification of toxic metals in the biological samples of living organisms is also an important procedure for clinical screening. In the health risk assessment, understanding reference values (RVs) in human biological samples sheds light on the level of exposure and plays a significant role in environmental pollution control.

An overview of the recent biomonitoring studies on heavy metal exposure is provided in Table 3. While different biological samples were utilized, the most extensively employed matrices for exposure biomonitoring of trace metals are blood and urine [119]. Overall, the referenced studies examined the association among human exposure, the concentrations of toxic metals in human biological samples and the activities of other biological markers. For example, a series of studies on toxic metal contamination around the Mahd Ad-Dahab gold mine area in Saudi Arabia revealed that healthy volunteers living near the mine exhibited significantly higher blood concentrations of heavy metals compared to the unexposed study subjects for control [100,120]. In addition, human biomonitoring can also help identify potential harmful exposures before clear adverse health effects manifest. In this aspect, the study of DNA damage in populations exposed to toxic metals has been utilized as a biomarker of adverse health effects [121].

4. Research gaps and conclusions

Accompanying the economic values, chromite mining and ore refining processes have been reported to cause significant environmental pollution. Hexavalent chromium (Cr(VI)), a chemical species of chromium, is particularly harmful, and can have distinctly adverse effects on humans, the environment, and its living organisms. This review highlighted the environmental pollution resulted from chromite mining and processing industries globally, and explained the probable toxic effects as well as toxicity mechanisms of the related toxic metals on exposed workers as well as other human population. The harmful impacts of chromite mining not only seriously pollute the environment, but it also put the workers who are directly involved and the adjacent neighbors in risk. Regarding the occupational exposure of workers to hazardous metals in mining contexts globally, there is a discernible research gap. These workers' prolonged exposure to toxic metals would probably increase the oxidative stress, which leads to a number of hereditary and non-genetic health consequences covering from respiratory disease to cancer. Therefore, evaluating the relationship between antioxidant biomarker levels and exposure to hazardous metals, as well as the rates of sickness and mortality among mining workers, is crucial.

It is important to implement certain changes regarding pollution reduction and occupational safety in hazardous mining environments. Firstly, the workplace environments need to adopt stringent safety laws governing the supply of suitable protective gear and regular training on safety precautions. Secondly, in order to continuously monitor and lower emissions from mining operations, it is advised to implement real-time pollution monitoring systems. Thirdly, there should be improvement made to the healthcare alternatives available to workers who are exposed, including support for any health issues brought on by pollution exposure, access to medical facilities, and routine health checkups.

CRediT authorship contribution statement

Changaiz Khan: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Riffat Naseem Malik:** Supervision, Investigation, Conceptualization. **Jing Chen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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