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## Chromium toxicity in plants: consequences on growth, chromosomal behavior and mineral nutrient status

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**Abstract:** Chromium (Cr) is a heavy metal of commercial importance; thus, significant amounts are released in wastewaters. The mobility and distribution of metals in the environment is related not only to their concentration but also to their availability in the environment. Most chromium (Cr) exists in oxidation states ranging from 0 to VI in soils but the most stable and common forms are Cr(0), Cr(III), and Cr(VI) species. Cr can have positive and negative effects on health, according to the dose, exposure time, and its oxidation state. Its behavior in soil, its soil-plant transfer and accumulation in different plant parts vary with its chemical form, plant type and soil physicochemical properties. Soil microbial community plays a key role in governing Cr speciation and behavior in soil. A number of factors have been identified to influence Cr toxicity on activated sludge, such as, pH, biomass concentration, presence of organic substances or other heavy metals, acclimation process, exposure time, etc. Inside plants, Cr provokes numerous deleterious effects to several physiological, morphological, and biochemical processes. Cr induces phytotoxicity by interfering plant growth, nutrient uptake and photosynthesis, inducing enhanced generation of reactive oxygen species, causing lipid peroxidation and altering the antioxidant activities. The present review describes the consequences of Cr toxicity on plants, including morphological, physiological and ultrastructural changes. This review also provides the basic concepts of Cr translocation and interaction with other essential macro- and microelements. Moreover, based on the available literature and current research scenario, this review suggests some possible management and remediation strategies to alleviate Cr toxicity and contamination in soil. It also provides valuable knowledge for further studies towards enhancement of soil phytoremediation and crops improvement. Therefore, there is a dire need to monitor biogeochemical behavior of Cr in soil-plant system.

**Key words:** Chromium, ecotoxicology, plant growth and nutrition, remediation, oxidative stress

### 1. Introduction

Heavy metals are significant environmental pollutants, and their toxicity is a problem of increasing significance for ecological, evolutionary, nutritional and environmental reasons (Saleem et al., 2020; Saleem et al., 2020). Anthropogenic activities such as industrial effluents, mining, and sewage sludge as well as fertilizers and pesticides application are the major sources of heavy metal accumulation in soils (Zaheer et al., 2020). Therefore, different food and fodder crops grown on metal contaminated soil can accumulate high concentration of metals that poses a severe threat to the human and animal health (Alatawi et al., 2022; Zaheer et al., 2022). Extreme

accumulation of potentially toxic elements in arable soil not only causes pollution of aquatic and terrestrial environments, but also escalates the likelihoods of human exposure with potentially toxic elements (Ahmad et al., 2022). The buildup of toxic metals in various compartments of the environment is hazardous for biotic health including humans due to bioaccumulation and biomagnification of heavy metals in living organisms. Chromium (Cr) is a potentially toxic metal which does not have any essential metabolic function in plants, and its excess concentration in the soil may cause toxic effects in plants and reduce the growth, photosynthesis, mineral nutrients, and quality of the crops (Ashraf et al., 2017; Ullah et al., 2015; Wuana and

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Okieimen, 2011). Cr is the 7th most abundant element, and 21st most abundant metal of the Earth's crust (Zaheer et al., 2020; Zaheer et al., 2020). In addition, Cr is one of the 18 core hazardous air pollutants (HAPs), 33 urban air toxicants, 188 HAPs (US EPA), and has been ranked 7th among the top 20 hazardous substances by the Agency for Toxic Substances and Disease Registry (Rizwan et al., 2019). It can easily infiltrate into groundwater and soil by natural and anthropogenic sources and poses serious threat to health of human-beings via its entry into the food cycle (Kumar et al., 2016). Most of the chromite resources are found in South Africa 84%, Zimbabwe 6%, Kazakhstan 5% and India 2% whereas Brazil, Russia, Finland, USA and Canada collectively have 3% of chromite (Chebeir et al., 2016). Cr has several oxidation states (-2 to +6), but hexavalent chromate [Cr (VI)] and trivalent chromite [Cr (III)] forms are the most common and stable in the natural environment (Li et al., 2018; Yu et al., 2018). Both these forms [Cr (III) and Cr (VI)] have different chemical, epidemiological and toxicological features; they are separately regulated by Environmental Protection Agency (EPA), which presents a distinctive noun (?) (Shahid et al., 2017). Higher concentrations of Cr (VI) inhibit germination and restrict root and shoot growth and the subsequent biomass accumulation, causing chlorosis, photosynthetic impairment, and reduction in chlorophyll production and protein synthesis, and finally can lead to plant death (Borna et al., 2016; Farid et al., 2019; Shahid et al., 2017). The biogeochemical behavior of Cr and its

sources in the agricultural land as well as its negative impacts on different organisms are presented in Figure 1.

Environmental contamination of Cr has gained substantial consideration worldwide because of its high levels in the water and soil originating from numerous natural and anthropogenic activities, and it is eventually accumulating in crops from contaminated soils and imparts severe health risks in humans via food chain contamination (Singh et al., 2013; Tang et al., 2019). Higher Cr levels in plants cause ultrastructural alterations (Ali et al., 2011; Sallah-Ud-Din et al., 2017), oxidative stress in plants, and increased electrolyte leakage (EL) and malondialdehyde (MDA) concentrations, whereas induced alterations in antioxidant enzyme activities such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) and ascorbate peroxidase (APX) (Zaheer et al., 2020; Zaheer et al., 2020). Previously, antioxidative enzymes played a significant role in the reduction of Cr phytotoxicity in *Lemna minor* (Sallah-Ud-Din et al., 2017), *Brassica napus* (Zaheer et al., 2020), *Vigna radiata* (Gautam et al., 2020), *Spinacia oleracea* (Zaheer et al., 2020), and *Triticum aestivum* (Ashraf et al., 2022) grown under excessive Cr concentrations. Under normal/natural conditions, ROS are involved in various essential metabolisms of plants such as regulation of stomatal conductance, signal transduction for programmed cell death, alleviation of seed dormancy, senescence, growth regulation, fruit ripening and initiation of defense metabolism under stress (Imran et al., 2020; Saleem et

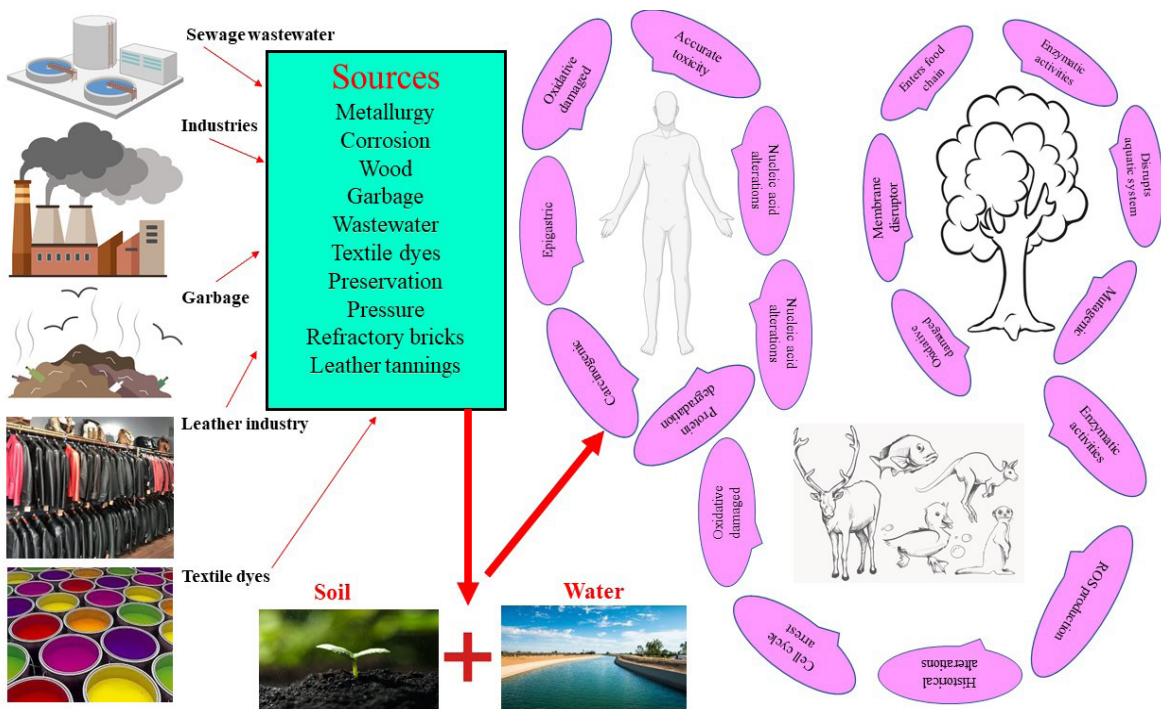


Figure 1. Biogeochemical behavior or Cr and its negative impacts on living organisms in soil-organisms system.

al., 2020). Enhanced generation of ROS provoke various biochemical and physiological disorders because of ROS interaction with lipids, proteins, enzymes and DNA resulting in membrane leakage and enzyme inactivation (Rehman et al., 2019). As a result, irreparable metabolic dysfunctions take place inside plant cells, thereby leading to cell death. Cr-induced ROS interact with biomolecules and the subsequent toxicity varies with the targeted tissue and the type of ROS. Some researchers even reported a dose dependent increase in ROS production as a result of Cr exposure (Grace Pavithra et al., 2019; Ranieri et al., 2020). Yu et al. (2018) reported that Cr (VI)-mediated enhanced ROS production and resulting oxidative stress associated with ultrastructural changes in root cells of *Oryza sativa*. The mechanisms of Cr tolerance and detoxification in higher plant species are presented in Figure 2. In higher plant species, Cr competes with other mineral elements. For instance, Cr toxicity may decrease Fe uptake from soil and its remobilization to plants leaves (Zaheer et al., 2020; Zaheer et al., 2020). Moreover, its antagonistic relationship with the uptake and translocation of Zn, P and S has been well documented (Kumar et al., 2016). Cr at higher concentrations is known to reduce the Fe, S and P contents in plants, thus additional supply of these nutrients is often suggested to reduce the accumulation of Cr within plant parts as these minerals are able to compete with Cr for carrier binding (Jobby et al., 2018; Junaid et al., 2016). In the present review, the potential effects of Cr toxicity on seed germination, seedling growth and biomass and productivity of plants were discussed. The consequences of

Cr toxicity on plant's mineral nutrient status and possible interactions of Cr with essential macro- and micronutrients were summarized. Moreover, we suggested some possible management strategies to mitigate Cr contamination in soils and also highlighted the guidelines for further future studies. This review provides a plausible link among Cr mobility/ bioavailability in soil, soil-plant transfer, toxicity and detoxification in plants. The review presents following six sections: (i) introduction stated above; (ii) Cr toxicity in the plants; (iii) plant mineral uptake and Cr toxicity; (iv) Cr interaction with secondary nutrients; (v) Cr interaction with nutrients; (vi) transportation of Cr; (vii) remediation strategies and future perspectives; and (viii) conclusion and thoughts.

## 2. Cr toxicity in plants

Cr is a noxious element that adversely impacts the metabolic processes in plants and reduces the growth and productivity of crops (Pradhan et al., 2017; Ugwu and Agunwamba 2020). Cr induced phytotoxicity is because of free radicals production which enhances degradation of biomolecules present in cells of plants (Ertani et al., 2017; Ranieri et al., 2020). In addition, Cr treatment showed cytotoxic, genotoxic impacts and hormonal imbalance which checks germination and development of plants and reduce dry matter production (Chebeir et al., 2016; Jobby et al., 2018). Excessive deposition of Cr in plant tissues showed adverse effects by modulation in cell division and cell cycle, water and minerals imbalance, alters enzymatic activities, nitrogen assimilation, degradation

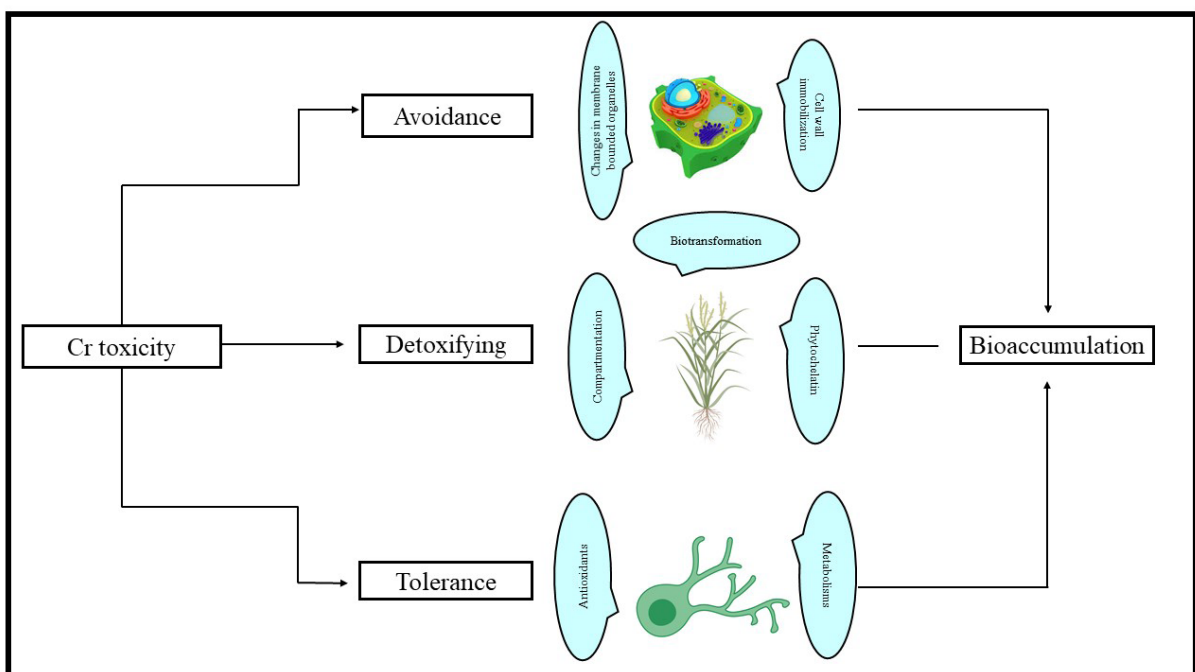


Figure 2. The mechanisms of Cr toxification and tolerance in the plants.

of chlorophyll, reduction in growth, free radicals generation and derangement of antioxidant defense system (Masciarelli et al., 2017; Ugwu and Agunwamba 2020). The toxic level of Cr can incite physical, chemical and molecular alterations in plants and its long-term retention in soil can reduce crop yield and grain quality (Shahid et al., 2017). Thirty-two plant species in which 94% species showed significant reduction in stem growth when exposed to 1000 mg kg<sup>-1</sup> hexavalent Cr (Junaid et al., 2016). Cr accumulation was recorded in the roots,

stems, leaves and seeds of wheat plants, indicating that this element is moving from down to up (da Conceicao Gomes et al., 2017). Cr interferes with several metabolic processes, resulting in impaired photosynthesis, inhibited plant growth, stunted development and plant death (Gill et al., 2015; Kalve et al., 2011; Kumar et al., 2016; Maqbool et al., 2018; UdDin et al., 2015; Zaheer et al., 2020). The negative impacts of Cr toxicity in various studies are presented in Table 1.

**Table 1.** Effects of Cr toxicity on plant growth and development under different Cr levels in the medium.

Crop	Media	Cr application	Effects of Cr on plants	Reference
<i>Triticum aestivum</i>	Aqueous solutions	(K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> ) 40, 80, 120 and 160 ppm	Inhibited root and shoot growth and seedling length with the increasing of Cr concentration in solution.	(Jamal et al., 2006)
<i>Glycine max</i>	Hoagland's nutrient solution no. 2	0, 0.05, 0.10, 0.50, 1.00 and 5.00 ppm of K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	Above 0.1ppm of Cr treatment, yield decreased, in both top and root parts. At 5 ppm Cr, toxicity appeared as wilting on the leaves. At harvesting stage, older leaves showed interveinal chlorosis and necrotic areas.	(Turner and Rust, 1971)
<i>Brassica napus</i>	Clay loam soil	(0, 100, and 500 µM)	Cr concentration of 100 and 500 µM reduced plant growth, root length, plant height, leaf area, number of leaves per plant and photosynthetic pigments. Malondialdehyde content and electrolyte leakage were considerably enhanced with increasing Cr concentrations in the medium.	(Afshan et al., 2015)
<i>Triticum aestivum</i>	Test solution (Petri dish)	25, 50, 75, 100 and 125 ppm of Cr (VI) K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	Cr toxicity significantly ( $p < 0.05$ ) influenced shoot and root length. Root growth was sharply inhibited under 100 ppm and 125 ppm of Cr Sugar content increased with increasing Cr concentration of 75 ppm. Total chlorophyll content and protein content were reduced with increasing Cr concentration.	(Datta et al., 2011)
<i>Lolium perenne</i>	Soil culture	50, 100, 250 and 500 IM Cr (VI) K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	Cr levels of 250 and 500 IM revealed toxic effects at the interveinal chlorosis in plant leaves. During 30-day time course treatment with 500 IM of Cr, these toxicity effects were shown in young leaves. After 45 days of exposure, the whole plant displayed necrosis and dried parts. Reduction in chlorophyll content was evident at 50 IM Cr. Reduction in chlorophyll a and b contents was recorded with increasing Cr treatments. Chlorophyll a/b ratio was considerably reduced under 100 IM of Cr after 15 days of culture. While chlorophyll a was more influenced than chlorophyll b upon plant exposure to 100 IM Cr for 30 days.	(Vernay et al., 2007)
<i>Solanum lycopersicum</i>	Hydroponic	50 and 100 mg/L (CrCb)	The increase of Cr concentration directly correlates with the depletion of length of roots, stems and branches, and total fresh weight of all parts excepting the fruits. Total yield was not affected but the number of fruits diminished.	(Moral et al., 1995)

Table 1. (Continued).				
Crop	Media	Cr application	Effects of Cr on plants	Reference
<i>Triticum aestivum</i>	Cr solution (500 ml pot <sup>-1</sup> )	0, 0.25, and 0.5 mM K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> (Sigma)	Plant morphological parameters such as kernel and root length and number of tillers were decreased. Cr stimulated oxidative stress and reduced the gas exchange attributes efficiency.	(Shakoor et al., 2014)
<i>Ocimum tenuiflorum</i>	10% Hoagland solution	0.0, 10.0, 20.0, 50.0 and 100.0 M of Cr(VI) K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> ·7H <sub>2</sub> O	The uptake of Cr by <i>O. tenuiflorum</i> significantly ( $p < 0.05$ ) affected plant growth and reduced plant biomass. Cr treatment at 100 M for 72 h decreased the total chlorophyll in plant body.	(Rai et al., 2004)
<i>Triticum aestivum</i>		2.0, 4.0 and 6.0 mM Na <sub>2</sub> CrO <sub>4</sub> for 48 h.	Germination percentage, radicles length and number were reduced. Cr stress mitigated wheat seed germination, and stunted radicle emergence and bud growth.	(Zhang et al., 2010)
<i>Raphanus sativus</i>	Nutrient solution	0.05, 0.10, 0.20, 0.30 and 0.40 mM K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> s Cr (VI) source	Less than, 0.10 mM increased ribonuclease activity. The higher concentrations of Cr decreased protein content in radish. Nonprotein nitrogen contents were reduced at optimal Cr concentration. Physiological parameters including plant height and dry weight was decreased as Cr increased in media.	(Tiwari et al., 2013)
<i>Arabidopsis thaliana</i>	MS solution, with specific nutrient elimination	0, 20, 40, 60, 80, 100 and 140 uM of(K <sub>2</sub> CrO <sub>4</sub> ) potassium chromate.	Certain beneficial effects of Cr were observed at 20µM. Under 20µM Cr, some genes involved in the regulation of metabolism, biogenesis of cellular components and protein function were modified. At 140 µM Cr, the functional gene categories which modified their expression included cell rescue, cellular transport and interactions with environment.	(López-Bucio et al., 2014)
<i>Triticum aestivum</i>	Hydroponic solution culture	0 and 100 µM of K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> (VI)	Under 100 µM of Cd, abnormal change in ultrastructure was observed such as the uneven swelling of chloroplast, as well as the size and quantity of starch granules in leaves were increased. Cr stress modified the root ultrastructure and increased the vascular size.	(Ali et al., 2013)
<i>Oryza sativa</i>	Control condition Petri plates	0, 2.5, 5, 10, 25, 50, 75, 100 and 200 mg/L	The study showed that 100 mg/L Cr could inhibit the morphological parameters. Cr increase in medium reduced the rate of biochemical process and caused imbalance as in nutrient uptake.	(Nagarajan 2014)
<i>Oryza sativa</i>	Soil	0, 100, 500 mg/Kg	Cr toxicity decreased the antioxidant enzymes activity due to the induction of oxidative stress.	(Hussain et al., 2018)
<i>Zea mays and Brassica nigra</i>	Soil condition	0, 5, 10, 20 and 30 ppm	All growth traits (plant height, dry matter, number of leaves per plant and chlorophyll content) were reduced with increasing Cr concentration.	(Kant et al., 2018)

## 2.1. Germination and seedling growth

Legumes are able to uptake Cr from soil and show various negative impacts like reduction in germination of seeds, biomass of seedlings and overall crop productivity. However, the extent of the damage varies with the crop species and the relative concentration of Cr. Besides its effects on seed emergence, Cr may also cause stunted bud growth, reduced radical length and shortening of coleoptiles (Adhikari et al., 2020; El Demerdash et al., 2019). Cr toxicity can inhibit seed germination (Kumar et al., 2016; Sinha et al., 2018), and its deleterious effects are more pronounced on the subsequent growth of emerging

seedlings (Ali et al., 2015; Yu et al., 2018). Wheat seeds germination and seedling growth are gradually inhibited by Cr (VI) toxicity (Danish et al., 2019). Sharma et al. (2016) reported that 0.5 mM Cr could inhibit 90% of seed germination in *Phaseolus vilgairs*. This might be due to the lesser nutrient and water transport. Jun et al. (2009) reported that *Lablab Purpureus* responded differently under varying levels of Cr toxicity (0, 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 mM) whereby the coleoptile growth and root elongation were reduced with increasing Cr concentration. Under Cr stress, seeds germination and seedlings growth were inhibited due to the excess movement of sugars

towards the embryo, which in turn altered the amylase and protease activities (Borna et al., 2016; UdDin et al., 2015). The forms of Cr revealed differently effects on various crops. Lopez-Luna et al. (2009) reported that the tannery sludge was less toxic than Cr III and Cr VI, and *A. sativa* germination was less affected as compared to *T. astivum* and *sorghum*. Seed coat prevents the excess penetration of Cr<sup>2+</sup> into the seed, however once the seed gets germinated, there is no barrier to protect the subsequent seedling from toxic ions, making Cr<sup>2+</sup> becomes more toxic for seedling growth (Coetzee et al., 2018; Ranieri and Gikas, 2014).

## 2.2. Root growth

Cr reflected delay in cell division, elongation and maturation of roots. The high Cr concentration inhibits root growth, while the lower levels of Cr (20–40 µM) stimulate it, as recorded for *Arabidopsis* seedlings (López-Bucio et al., 2014). Martinez and Gil (2015) reported that Cr at 100 µM severely inhibited root growth due to the reduction of cell division and the primordial formation. Reduction of root growth under toxicity of Cr (VI) was mainly due to the inhibition of root cell elongation and reductions in tissue uptake of water and nutrients (Chebeir et al., 2016; Jobby et al., 2018). Major portion of Cr retains in plant root cell wall, representing 83.2% as previously reported (Liu et al., 2009). Cr toxicity mainly impairs the primary growth of the emerging seedlings of *Triticum asstivum* and *Arabidopsis thaliana* (López-Bucio et al., 2014; Rellán-Álvarez et al., 2006). Moreover, Cr accumulation was observed in the root cells of various crops, including rice (Hussain et al., 2018), barley (Ali et al., 2011), *Vicia faba* (Khadra et al., 2019), wheat (Zhang et al., 2010) and *Brassica napus* (Zaheer et al., 2020). (Sundaramoorthy et al., 2010) reported that Cr (VI) irregularly regulates the cell cycle and cell division process, causing inhibition of the root growth. Therefore, Cr is more toxic for the growth of plant roots and its sequestration in root vacuoles may happen due to its precipitation as insoluble salts or due to its immobilization with sugar, celluloses and hemicellulos (Akinci and Akinci 2010; Chebeir et al., 2016; Danish et al., 2019; Mohanty and Patra 2011; Riaz et al., 2019).

## 2.3. Shoot growth

Like other plant parts, shoot growth is sensitive to Cr toxicity. This decrease in shoot growth and height can be due to the Cr-reduced root growth and development, resulting in decreased water and nutrient translocation to the above ground plant parts. Moreover, increased Cr transport to shoot tissues can directly interact with sensitive plant tissues (leaves) and processes (photosynthesis), which affect cellular metabolism of shoots, thereby reducing plant height (Ali et al., 2018; Zaheer et al., 2020). The pathway for Cr (VI) movement from root to shoot is an active mechanism and using essential nutrient transporters (Ranieri et al., 2020). Cr

concentration predominantly is low in stem as compared to root (Medda and Mondal, 2017). Toxic effects of Cr on the plant shoot growth were recorded in various plant species (Nath et al., 2005; Maqbool et al., 2018; Nafees et al., 2018). Gill et al. (2015) reported that the reduction of shoot growth could be due to the ultrastructural changes in plant organs. Different levels of Cr showed variable effects on plant shoot in different crops. For instance, the shoot growth of maize and wheat was stimulated at 0.5 ppm and 0.25 ppm of Cr (III), respectively, but it was inhibited at 5 ppm and strongly restricted at 50 ppm for both crops (Ali et al., 2015; Datta et al., 2011). Similar results were also observed in corn (James and Bartlett 1984), who reported that 10 mmol of Cr caused a stunted plant shoot growth as compared to control. The reduction in shoot elongation and biomass accumulation might also be due to the restricted root growth, which results in reduced transport of water and nutrients to the above ground plant parts. Moreover, Cr transport to the aerial plant parts has direct impacts on the cellular metabolism of shoots may lead to the reduction of shoot elongation (Liu et al., 2009; Ahmad et al., 2019).

## 2.4. Plant leaf

Cr can indirectly affect the foliar plant parts and is responsible for reducing the photosynthetic pigments and protein contents in plant leaves (Li et al., 2018; Patra et al., 2019). (Afshan et al., 2015) reported that 100 and 500 µM of Cr could decrease the content of chlorophyll in *B. napus*. Vajpayee et al. (2000) reported that Cr stress treatment above 1 µM inhibited the activities of ALAD and NR, enhanced ALA levels, and reduced chlorophyll and protein contents in *Nymphaea alba*. Moreover, radish crop showed marginal chlorosis, which would be able to spread to the upper parts after 5 days of exposure to Cr at 0.30 and 0.40 mM of K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> (Tiwari et al., 2013). The presence of Cr (VI) seriously affected the plant leaves, turning them to become yellow and wilted due to the loss of petioles turgor. The number and size of leaves was also reduced (Kimbrough et al., 1999). The chlorosis of leaves under Cr stress may be due to the decreased concentrations of N, P, K and Fe in leaves tissues (Kassaye et al., 2017; Medda and Mondal, 2017; Shanker et al., 2005). The photosynthetic rate and stomatal conductance rate observed were minimized due to Cr stress in barley (Ali et al., 2011). Cr is also deformed the ultrastructure of chloroplast, causing deleterious effects on biochemical activities and reduction in the photosynthetic pigment content in plant leaves (Afshan et al., 2015; Ali et al., 2011; Zaheer et al., 2020).

## 2.5. Biomass and yield

High plant biomass is the first prerequisite for high plant yields. Cr is well-reported to induce noxious effects to several physiological and biochemical processes, consequently, plant yield and productivity are equally compromised (Ali et al., 2018; Kumar et al., 2016; Zeng



et al., 2011). In *O. tenuiflorum*, Cr toxicity at 100 mM significantly decreased the plant biomass as compared to the control (Rai et al., 2004). Moreover, 20 and 40  $\mu\text{M}$  Cr positively enhanced the shoot fresh weight as compared to control, whereas 80–140  $\mu\text{M}$  Cr reduced the biomass production of *Arabidopsis thaliana* (López-Bucio et al., 2014). Similarly, the plant root and shoot were suppressed at Cr concentrations of 0.5 mM. The biomass and seed yield were also reduced 75%–80% at 0.1 mM Cr. The seed yield of *Triticum aestivum* and *Cucumis sativus* was also reduced by 70% at 0.2 mM Cr (VI) (Datta et al., 2011; Ali et al., 2015). Ali et al. (2015) reported that the morphological parameters of wheat plants, such as root growth, number of tillers per plant and grain length, were significantly reduced with increasing Cr concentration. Cr toxicity may influence the total biomass and yield as a consequence of poor production and partitioning of assimilates (Luna et al., 2009; Chebeir et al., 2016; Hussain et al., 2018; Lopez- Nafees et al., 2018). Cr-induced decrease in plant development, growth and yield can be due to several factors: reduced water and nutrient uptake, decrease in cell division and cell division rate, imbalance in nutrient uptake and translocation, inefficiency of plants for selective inorganic nutrient uptake, enhanced production of reactive radicles and the resulting oxidative stress, substitution of essential nutrients from key molecules and ligands, and oxidative damage to sensitive plant tissues such as mitochondria, pigment contents, DNA, RNA, lipids etc. (Chen et al., 2017; Maqbool et al., 2018).

## 2.6. Induced oxidative stress

Plants being sessile organism are often exposed to heavy metal stress as they have no choice to escape from unfavorable environmental conditions (Kamal et al., 2022; Rehman et al., 2020; Saleem et al., 2020). Under Cr exposure, plants suffer through morphological biochemical alterations because of the imbalance between the production and removal of free radicals also known as an oxidative burst (Ali et al., 2011; Sallah-Ud-Din et al., 2017; Zaheer et al., 2020). Free radicals are generated in different organelles such as chloroplast, peroxisome and mitochondria as a byproduct of different biochemical processes. The Cr metal disrupts enzyme active sites by attaching with functional groups and changes enzymatic activities. Hence, cations disruption from binding sites of enzyme disturbs equilibrium of cells and generates free radicals (Irshad et al., 2021; Saleem et al., 2021). Cr stress exhibits enhanced ROS production and damage in biological membrane (Tripathi et al., 2012), by disruption in DNA and membrane lipids. Cr mediated reduction in essential amino acids showed significant decrease in nitrogen and protein contents. Escalated generation of ROS in plants under Cr toxicity promotes damage of pigments, nucleic acid, proteins and increases lipid peroxidation (Danish et al., 2019; Maqbool et al., 2018).

Significant rise in ROS was observed with more MDA contents under chromium toxicity. Cr deactivates plant defense mechanisms and increases the formation of ROS observed in wheat (Adrees et al., 2015). Various studies revealed that higher concentration of Cr is responsible for induced MDA (Ali et al., 2011; Ali et al., 2011). Under Cr stress, the production of ROS species ( $\text{H}_2\text{O}_2$  and  $\text{O}^{2-}$ ) in various plant species were induced due to Cr stress (Zaheer et al., 2019). Panda and Choudhury (2005) found that lipid peroxidation and MDA content increased with the increase of Cr (1, 10, and 100 mM) in wheat plant. In maize, Cr stress (30, 60, 90, 120, and 150  $\mu\text{mol L}^{-1}$ ) initiated the generation of lipid peroxidation in the form of (MDA),  $\text{H}_2\text{O}_2$  and thiobarbituric acid reactive substances (Adhikari et al., 2020; Nafees et al., 2018). Eleftheriou et al. (2015) stated that Cr VI specifically damaged the roots of *Arabidopsis thaliana*, and the oxidative species, including  $\text{H}_2\text{O}_2$  and  $\text{O}_2^-$  were formed in roots upon exposure to 100 $\mu\text{M}$  of  $\text{K}_2\text{Cr}_2\text{O}_7$ . The Cr toxification inducing oxidative stress in the plant cell as well as the actions of antioxidant activities are presented in Figure 3.

## 2.7. Antioxidant enzymes

The maintenance between production and ROS deletion is needed, which can be obtained by regulation in enzymatic and nonenzymatic antioxidants generation (Ahmad et al., 2019; Bah et al., 2011; Tripathi et al., 2012; UdDin et al., 2015). Plants with an effective antioxidant system are able to control high concentration of Cr. The nonenzymatic antioxidants are composed of less molecular weight compounds like carotenoids, ascorbic and phenolic acids, flavonoids, glutathione etc. which function as redox buffer and affect plant growth and maturation by alteration in various cellular processes. Reduced glutathione functions as an antioxidant by suppression of free radicals and participates in ascorbate-glutathione cycle and eradicates damaging peroxides. The level of antioxidant activities against the toxic concentration of ROS depends upon the ROS type and its generation (Parveen et al., 2020; Saleem et al., 2020; Alatawi et al., 2022; Ali et al., 2022; Ashraf et al., 2022; Dominic et al., 2022). Various antioxidant compounds work in coordination with each other to decrease the toxic effect of ROS. In higher plants, the activities of antioxidants can increase or decrease against the Cr toxicity in the soil (Ali et al., 2022; Ali et al., 2022; Zaheer et al., 2020). Zaheer et al. (2019) indicated that the addition of different levels of wastewater (0%, 33%, 66%, and 100%) in the natural soil induced the oxidative damage in the roots and leaves of in *Spinacia oleracea*. They also revealed that the severe Cr toxicity in soil caused a significant ( $p < 0.05$ ) decrease in the activities of various antioxidants. On the other hand, Cr toxicity in the soil significantly enhanced the activities of various antioxidants in the roots and leaves of *Spinacia oleracea* plants (Zaheer et al., 2020). Therefore, the decrease or increase of the

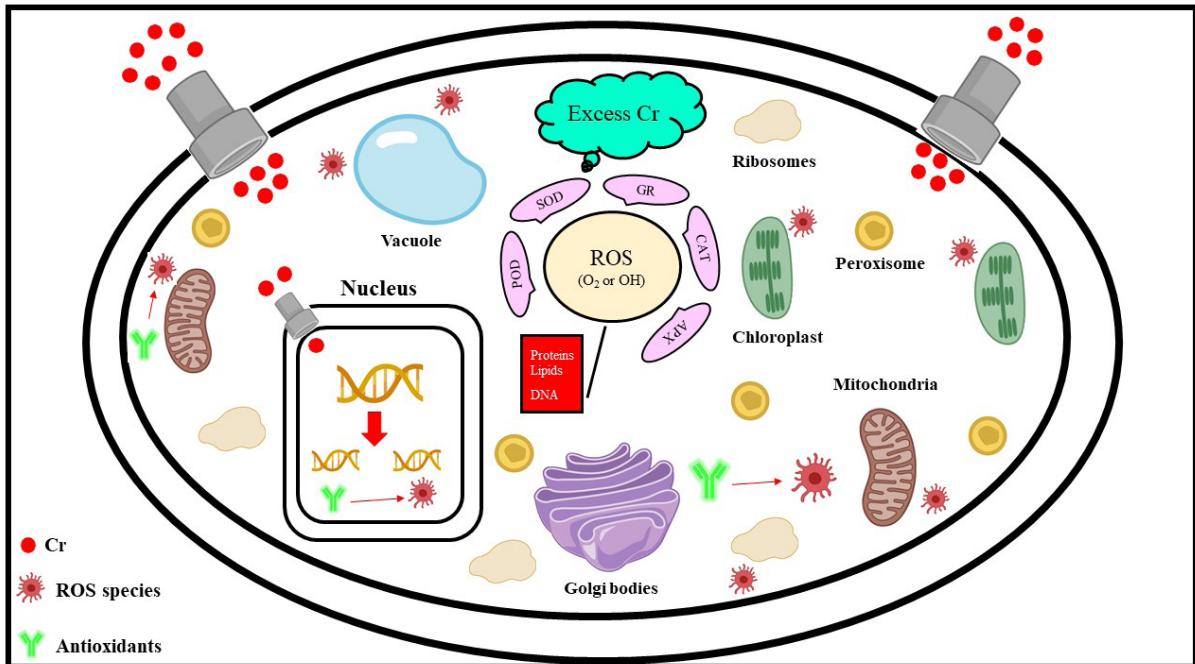


Figure 3. Oxidative damage and responses of antioxidant compounds in the plant cell.

antioxidant activities against Cr stress could be due to the Cr contents in the soil, growth medium and treatments (Adhikari et al., 2020; Ali et al., 2011; Liu et al., 2008).

### 2.8. Photosynthesis

Excessive Cr negatively impacts photosynthesis by affecting enzymes of Calvin cycle, thylakoid membrane and photosynthetic electron transport (Rehman et al., 2019; Saleem et al., 2020; Saleem et al., 2019; Ulhassan et al., 2019). The presence of Cr showed reduction in pigment biosynthesis, inhibition in net photosynthetic rate, stomatal conductance, electron transport chain, fixation of carbon dioxide, photosynthetic phosphorylation, plastids structure and negatively affects light/dark reactions (Chen et al., 2017; Hussain et al., 2018). Moreover, Cr toxicity induces negative impacts on plant development (UdDin et al., 2015), antioxidant compounds (Liu et al., 2008), stomatal conductance (Maqbool et al., 2018) and water use efficiency (Hussain et al., 2018). Previous studies reported that the toxic level of Cr in the soil reduced photosynthetic pigments in the leaves of *Brassica rapa* (Ali et al., 2018), *Triticum aestivum* (Subrahmanyam 2008) and *Brassica napus* (Zaheer et al., 2020). The toxic level of Cr in the soil may also cause ultrastructure alterations in the chloroplast and other membrane bounded organelles which in turn result in the reduction of photosynthetic pigments (Rai et al., 2004; Zaheer et al., 2019). Under Cr stress, such these alterations have been observed in *Brassica napus* (Afshan et al., 2015), *Lolium perenne* (Vernay et al., 2007), *Amaranthus viridis* (Liu et al., 2008) and *Pisum sativum*

(Bishnoi et al., 1993).

Cr toxicity in the soil also affects light and dark reactions via inducing alterations in the thylakoid membrane (Kumar et al., 2016; Ertani et al., 2017). Under severe Cr toxicity in the soil, excess of electrons is generated during the photochemical processes which are not used in the carbon fixation cycle. Furthermore, the toxic levels of Cr cause redox changes in Cu and Fe heme group, which is the main factor of photosynthesis reduction in plants (Masciarelli et al., 2017; Shahid et al., 2017). The Cr stress-induced decrease in photosynthesis in plants may also be due to the overproduction of ROS in the soil through oxidation reduction mechanisms (Ugwu and Agunwamba 2020), which ultimately leads to induction of oxidative stress and reduction of plant growth, biomass and yield (Farid et al., 2019; Vernay et al., 2007).

### 2.9. Genotoxicity

Cr-induced genotoxicity has been extensively studied in yeast and animals in terms of DNA inter- and intrastrand crosslinks, DNA-protein crosslinks, DNA-strand breaks, DNA adducts, dysfunctional DNA transcription and replication, dysregulated DNA repair mechanisms, alteration of survival signaling pathways, genomic instability, oxidized bases, abasic sites, microsatellite instability, and the epigenetic/genetic changes (Vernay et al., 2007). Despite of the critical significance of Cr ecotoxicity, there exist considerable gap of information and understanding in plants compared to that in animals and human beings about the mechanisms of Cr genotoxicity.

Cr is unique unlike other metals because of its ability to interact primarily and directly with DNA, forming DNA-DNA crosslinks and DNA-protein (Kumar et al., 2016). Of what is known, Cr (VI) is considered a highly carcinogenic and mutagenic pollutant, while other metals are regarded slightly mutagenic. Cr toxicity in plant cells causes chromosomal abnormalities, impairment of cell division, cell cycle arrest, repression of antioxidative enzymes and induction of micronuclei formation (Kimbrough et al., 1999; Schiavon et al., 2012). However, Cr-induced cytotoxic, genotoxic and mutagenic effects vary in different plants and organs, which remains an area to be explored. This inconsistency can be due to differential distribution of Cr within cell compartments (Shahid et al., 2017), by variation in the intracellular contents of the particular chemical form. For example, previous studies reported that Cr toxicity provoked a mutagenic effect in *Zea mays* (Erenoglu et al., 2007), and other plant species (Oliveira, 2012).

### 3. Plant mineral nutrients and Cr toxicity

Cr having a close structural resemblance to many of the essential elements, can influence the mineral nutrient status in plants (Ali et al., 2018; Dube et al., 2003). Cr is a nonessential element; thus, plant body has no specific mechanism for its uptake (Gardea-Torresdey et al., 2004; Tiwari et al., 2013). Having a similar structure with sulfur (S), phosphorus (P) and iron (Fe), Cr may interfere with the uptake, translocation, and accumulation of these nutrients (Dube et al., 2003; Ulhassan et al., 2019; Zaheer et al., 2020). It easily interrupts the uptake of the essential elements required for the plant life cycle (Sundaramoorthy et al., 2010). Generally, the nutrients availability also depends on root structure and element concentration in medium (Chandrasekhar and Ray, 2017; González-Pérez et al., 2004). Tiwari et al. (2013) reported that Cr affects the plant metabolism via interfering with the essential nutrients or via activating enzymes at the functional sites.

#### 3.1. Chromium and Nitrogen

Nitrogen (N) is a key element for plants to secure their life cycle. Plants uptake N in the form of ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ) ions. It is possible that both forms of N may affect the uptake and translocation of Cr (Ulhassan et al., 2019; Zaheer et al., 2020). Cr (VI) at lower concentrations is able to fix atmospheric N by assisting the formation of nodules. However, at higher Cr levels, the potential of the developed nodules to fix N could be impaired, as previously recorded in Pea (Bishnoi et al., 1993; Handa et al., 2017). Both forms of Cr (VI) and Cr (III) could limit the availability of N, reduce chlorophyll content, and disturb photosynthesis and respiration process in plants (Ali et al., 2013). Cr (VI) severely affects the activity of photosystem I as compared to photosystem II (Bishnoi et al., 1993). Protein deficiency in plant leaves,

due to lack of N, was observed in rice and wheat under Cr toxicity (Nagajyoti et al., 2010). The interaction between inorganic N and heavy metals such as Cr is also influenced by the specific plant species and its growth stage (Ashraf et al., 2017). Sulfur intake in plants has been documented to decrease due to the rising level of Cr in plants (Wuana and Okieimen, 2011). Nitrogen availability is also influenced by the N source. For instance,  $\text{Ca}(\text{NO}_3)_2$  is able to reduce Cr accumulation in plants as compared to the ammonical form  $(\text{NH}_4)_2\text{SO}_4$  (Ali et al., 2013).

#### 3.2. Chromium and phosphorus

Phosphorus is the second most important nutrient after N (Rana et al., 2020). It has a key role in several metabolic processes in plants. Cr (VI) is structurally similar to P. Therefore, Cr interferes with the uptake, translocation and/or accumulation of P, causing P deficiency (Ma et al., 2020; Zhu et al., 2016). In water melons, the reduced level of Cr increased the uptake of P in order to compete with other metals such as Zn and Fe (Dube et al., 2003). It has been reported that there is a competition between Cr (VI) and P to enter into plant cells (James and Bartlett, 1984). Higher levels of Cr result in reduced plant growth and P concentration in plant leaf tissues. Likewise, the leaf area is reduced and the light-dependent reactions are hindered (Kumar et al., 2016; Pradhan et al., 2017). In several cases, P concentration was reduced in roots and increased in younger leaves at 0.2 mM Cr, but it decreased beyond this level in *Citrullus* (Dube et al., 2003). High Cr concentration antagonistically affected root growth and induced the expression of genes responsive to Pi scarcity (López-Bucio et al., 2014).

#### 3.3. Chromium and potassium

Cr and Potassium (K) interaction is also antagonistic like other macronutrients, where 0.1 ppm of Cr was able to decrease K level in soybean shoots (Turner and Rust, 1971). Sundaramoorthy et al. (2010) reported a decreased uptake of K with increasing Cr (VI) level in flooded rice plants. The main effects of Cr toxicity on the mineral nutrition are presented in Table 2.

### 4. Chromium interaction with secondary nutrients

The translocation of secondary nutrients under Cr toxicity differs from crop to another. Cr toxicity severely decreases Ca content in perenne leaves, resulting in declined oxidation of water and electron flow at the photosynthesis process because Ca is a necessary cofactor for  $\text{O}_2$  evolution and has a role in water oxidation (Vander Meulen et al., 2004). Levels of Cl and Na were enhanced at 0.5 mM and 0.1 mM of Cr, whereas both levels of Cr reduced Ca and Mg levels in *Solanum nigrum* and *Parthenium hysterophorus*. (Gardea-Torresdey et al., 2004). The interaction of Cr with Ca and Mg varies based on the growing media. Turner and Rust (1971) observed that in soybean, the total contents of Ca and Mg in the water culture were reduced with

**Table 2.** Cr toxicity effects on the mineral nutrition in higher plants.

Cr form	Interaction	Plant nutrient	Comments	References
Cr (VI)	Antagonistic →	Nitrogen	Cr reduces the availability of nitrogen from the form of $(NH_4)_2SO_4$ .	(Johnson et al., 1980; Ali et al., 2013)
Cr (VI)	Antagonistic →	Phosphorus	Cr reduces P availability otherwise there is a tough competition between these ions.	(Chatterjee and Chatterjee 2000; López-Bucio et al., 2014)
Cr (VI)	Antagonistic →	Potassium	Cr suppresses the ability of K in soils, particularly in irrigated lands.	(Barcelo et al., 1985; Sundaramoorthy et al., 2010)
Cr (VI)	Antagonistic →	Calcium		(Vander Meulen et al., 2004)
Cr (VI)	Antagonistic →	Sulfur		(Schiavon et al., 2012)
Cr (VI)	Antagonistic →	Magnesium	In certain soils, Mg availability is high because Cr interferes with plant cells to uptake Mg.	(Moral et al., 1995; Vander Meulen et al., 2004)
Cr (VI)	Synergetic ←	Chlorine	Cr enhances the availability of applied Chlorine near root exudates.	(UdDin et al., 2015)
Cr (VI)	Synergetic ←	Manganese	Cr increases the uptake of Mn by plants. However, Mn is reduced by Cr toxicity.	(!!! INVALID CITATION !!! {}; Barcelo et al., 1985)
Cr (VI)	Synergetic ←	Boron	Cr increases B availability in both soil and water culture, and usually Cr does not interrupt its translocation.	(Barcelo et al., 1985; Turner and Rust 1971)
Cr (VI)	Antagonistic →	Copper	Cu availability in plant cells is low under Cr toxicity	(Dube et al., 2003; Kováčik et al., 2013)
Cr (VI)	Antagonistic →	Zinc		(Chatterjee and Chatterjee 2000; Kováčik et al., 2013; López-Bucio et al., 2014)
Cr (VI)	Antagonistic →	Iron	Fe availability is reduced under Cr toxicity. However, there is a tough competition between these metals.	(Barcelo et al., 1985)

increasing Cr level above 0.1 ppm in roots tissues, whereas under soil conditions, the contents of Ca and Mg increased as Cr might interfere with plants ability to uptake these elements. Vajpayee et al. (2000) discovered that Cr VI can displace Mg from the enzymes active sites, resulting in inhibition of chlorophyll formation. Moreover, Ca content in tomato roots was reduced with increasing Cr although the Ca content in top plant parts was not influenced by Cr toxicity [40].

Cr is structurally similar to sulphate (Dube et al., 2003; Ulhassan et al., 2019). The interaction between Cr and S is antagonistic. The consumption of S in plants has been documented to be reduced because of the increase in Cr (Sullivan et al., 2000; Burton et al., 2008). The translocation of S from plant roots to shoots was also reduced, resulting in higher S contents in root cells as compared to floral parts (Sullivan et al., 2000; Dube et al., 2003). Moreover, sulphate content in growth medium minimizes Cr (VI) uptake by plant (Oliveira, 2012).

### 5. Chromium interaction with micronutrients

Higher Cr concentrations reduce nutrients as well as the intake of vital elements. The high level of Cr (VI) could alter the normal absorption of Mn, Cu and Zn,

which can lead to a nutrient deficiency and slow plant development (Dube et al., 2003; Ulhassan et al., 2019). Cr enhanced the Mn uptake but reduced the levels of Fe, Cu, Zn, and S in watermelon leaves (Chen et al., 2017). Moreover, the application of Cr at 0.4 mM increased Zn concentration in stem and root cells but decreased Zn in middle leaves (Zaheer et al., 2019). Cr stress also reduced the translocation of P, S and Zn from plant root to leaves (Chatterjee and Chatterjee 2000). However, the translocation of Mn, Cu and B was less affected. Zn-lysine foliar application also reduced Cr hazards and protected the plants via improving oxidative defense mechanisms (Afzal et al., 2018). Cu and Zn were reduced in the root and shoot of *Chamomile* plants (Kováčik et al., 2013).

Cr (VI) interrupted the mineral nutrition by interfering with the uptake and translocation of Fe, Ca, and Mg in *Lolium perenne* (Vernay et al., 2007). Toxicity of Cr (VI) is responsible for the depletion and unavailability of Fe in leaves of radish and spinach (Sehrish et al., 2019; Tiwari et al., 2013), thus leading to Fe deficiency (Chatterjee and Chatterjee 2000). Moreover, Cr stress induced Mn deficiency in *Vigna Radiata* and *Brassica oleracea* (Karuppanandian et al., 2006). On the other hand, in higher plants, Cr (VI) increased the Mn uptake and

translocation in the younger leaves of *Lolium perenne* and *Citrullus Vulgaris* (Dube et al., 2003; Ducic and Polle, 2005). A negative correlation of Cr with Fe, Zn and Cu was also recorded (Barcelo et al., 1985). Fe acts as a signal that can be interpreted through the plant root and induces molecular mechanisms that could possibly alter cells division and differentiation through the action of certain transcription factors (López-Bucio et al., 2014). Furthermore, the presence of Fe in growth media can directly reduce Cr (VI) translocation by plant (Handa et al., 2017).

Previous studies also reported synergistic relations between Cr and some essential nutrients such as Cu, Mg and Mn (Vernay et al., 2007; Wei-Dong et al., 2007). In the aerial parts of *Citrullus*, the excess of Cr was also inhibited by the absorption of Cu, whereas Cu concentration was higher in leaves than in roots. Adding Cr to the nutrient solution resulted in reduced Cu level in leaves and increased level in stems and roots (Dube et al., 2003). Hence, under Cr toxicity, a tough completion is present between Cr and essential nutrients required for plant growth and yield production. (Zeng et al., 2011) also indicated that Cr stress limits the movement and accumulation of major and microelements in rice crop.

## 6. Transportation of Cr

### 6.1. Cr uptake by the plant

The roots of plant secrete various organic acids, which acts as ligands and can change insoluble metals present in the soil into soluble forms. Hexavalent Cr is actively taken up by the plasma membrane by involving phosphate and sulfate transporters whereas trivalent chromium enters via cation exchange sites present in plant's cell wall (Zaheer et al., 2022). Cr dispensation and translocation in plants depend on oxidation state of Cr ions, its amount in the nutrient medium and species of plants (Datta et al., 2011), and the Cr content in roots is hundred times higher compared to the shoots (Ertani et al., 2017; GracePavithra et al., 2019). Plants restrict metals and metalloids accumulation in the less susceptible organelles to prevent its degradation at level of cells (Masciarelli et al., 2017). The presence of electron-dense particles in the cell wall is a defense strategy of cells for heavy metal toxicity. Deposition of electron-dense particles in between cell wall and cell membrane, vacuoles, plastids, between endoplasmic reticulum cisternae and cytosol of seedlings of *Arabidopsis* have been reported due to hexavalent Cr exposure (GracePavithra et al., 2019). The accumulation of Cr in root cells vacuoles might be due to the sequestration of Cr as a defensive process. The transport of Cr from roots to the leaves of plants was not observed as hexavalent is converted to trivalent Cr in cells of plants and it binds with cell wall, which inhibits its transfer in different plant tissues (Jobby et al., 2018). Cr uptake by the plant organs

mainly depends upon the Cr level in the soil, plant species and growth medium (GracePavithra et al., 2019; Madhu and Sadagopan 2020). Cr (III) is passively transported to the aboveground part of the plant; while Cr (IV) is actively transported to the plant parts (Ahmad et al., 2019). It was also reported that Cr (IV) is not easily transported to the plant parts due to the subsequent assimilation pathways and its interference with some essential nutrients, which may affect its transportation to the aboveground plant parts (Dube et al., 2003). Furthermore, Cr (IV) has a high soil-plant transfer index and is also affected by metabolic inhibitors, which make it difficult to be up taken by the plants (Kimbrough et al., 1999; Ali et al., 2018).

### 6.2. Cr Absorption by the plant root system

Cr is the slightest moveable metal among all different heavy metals (Tripathi et al., 2012; Eleftheriou et al., 2015; UdDin et al., 2015). In addition, the amount of Cr in the roots is found to be 100 times more than that present in the aboveground parts of the plants (Jun et al., 2009). The trend of Cr uptake/absorption in various plant parts (roots > shoots) has been previously observed in *Brassica napus* (Zaheer et al., 2020), *Arabidopsis thaliana* (Eleftheriou et al., 2015), *Helianthus annuus* (Farid et al., 2018) and *Typha angustifolia* (Bah et al., 2011). Previous studies reported accumulation of large amount of Cr in the vacuoles of plant root cells (Liu et al., 2009). Due to the formation of some chemicals inside the plant tissues, the transportation of Cr from the roots to the aboveground parts is limited (Gardea-Torresdey et al., 2005). Another possible reason behind this mechanism is the formation of Cr (III) in plant cells (Shahid et al., 2017).

### 6.3. Transportation of Cr to the aboveground parts

Heavy metals such as Cu (Saleem et al., 2020), Pb (Madhu and Sadagopan, 2020), and Zn (Murakami and Ae, 2009) have the ability to penetrate into the plant tissues and could be transported to the aboveground plant parts through the vascular bundle channels. The group of gene family involved in these mechanisms may include NRAMP, HMA and CDF (Nagajyoti et al., 2010). These gene families are helpful in metal transport/accumulation and help in the tolerance of the plants to stress conditions. However, more studies are still needed to validate the functional role of these gene families in various plant species. Cr (IV) usually needs active mechanisms to be transported into the aboveground plant parts. For the transportation of Cr to the aboveground plant parts, Cr usually uses the channels of Fe and S for its proper translocation into the plant tissues (Kumar et al., 2016).

### 6.4. Cr-hyperaccumulator plants

Hyperaccumulator plant species are used to uptake heavy metal contents from the metal contaminated site (Saleem et al., 2020; Saleem et al., 2020). More than 500 different plant species are known to be hyperaccumulator for various toxic metals (Rehman et al., 2019; Usman et al.,

2018). Hyperaccumulators are simply defined as the plant species with high potential and capability to uptake metal contents by their body parts without any anxious effects. Hyperaccumulators also have a translocation factor more than 1 and have a fast growth rate and a high biomass production (Kamran et al., 2020; Lessl et al., 2015). Due to the growing population and industrialization, phytoremediation became more important and prevalent due to the pollution of large agricultural areas (Cristaldi et al., 2017; Wuana and Okieimen 2011). Though various plant species proved high potential to tolerate and survive heavy metal stress environments, only few plant species were identified to tolerate Cr stress in the environment. Cr-hyperaccumulator plant species should produce more than 100 mg kg<sup>-1</sup> in their dry biomass. Some plant species which have been recognized as Cr-hyperaccumulator species include *Leersia hexandra* (Zhang et al., 2007), *Prosopis laevigata* (Buendía-González et al., 2010), *Pteris vittate* (Kalve et al., 2011) and *Nopalea cochenillifera* (Adki et al., 2013).

## 7. Remediation strategies and future perspectives

The treatment of wastewater or industrial effluent containing trivalent or hexavalent chromium ions is required prior to its discharge into the environment or its conversion into the less hazardous form to avoid its health-related adverse effects on living organisms. The conventional techniques like chemical transformation, oxidation-reduction reactions, coagulation, photocatalytic and electrochemical reduction, membrane technology, adsorption, bioremediation and nanotechnology etc. have been exploited to remove chromium from effluent or contamination sites (Imran et al., 2021; Yasmin et al., 2021). The main disadvantage related with all the above stated approaches is expensive application procedure, high energy demand, complicated process and sludge production which may cause secondary pollution. Chemical reduction process is not suitable for treatment of Cr polluted soil containing industrial effluents as it is exhaustive process in which reducing agents are mixed in the polluted soil (Hassan et al., 2021). Solidification is another method which fixes Cr in the mixture by supplementing fly ash, cement and other solid waste which gives durability to Cr in environment. Adsorption of hexavalent Cr can be increased by addition of inorganic substances like elemental sulfur (Lessl et al., 2015; Usman et al., 2018).

Phytoremediation is used by the hyperaccumulator plants which transform the toxic metals into lesser toxic and immobile forms. The mechanism behind the Cr hyperaccumulators is the presence of high-affinity ligands such as peptides, amino acids and organic acids that chelate chromium and sequesters them into the vacuole (Ranieri et al., 2020). Bioremediation of Cr containing effluents by

using microorganisms have gained significance due to its low-cost, high efficiency, wide availability of microbes, universal in application, green and publicly acceptable treatment technology. Microbes show significant function in transformation of Cr hexavalent to trivalent form due to their high sorption capacity. The removal of hexavalent Cr by microbes has three phases (I) attachment of hexavalent Cr to surface of cells (II) transport of hexavalent Cr inside cells and (III) conversion of hexavalent to trivalent form (Chebeir et al., 2016; Wuana and Okieimen, 2011). Several bacterial strains like *Pseudomonas*, *Escherichia*, *Enterobacter*, *Aeromonas*, *Achromobacter*, algal species like *Spirogyra*, *Chlorella vulgaris*, fungal species such as *Rhizopus arrhizus*, *Penicillium chrysogenum*, *Rhizopus oryzae* and yeast strains such as *Rhodotorula pilimanae*, *Yarrowialia polytica*, and *Rhodotorula mucilaginosa* have been reported for their Cr degradation ability (Adrees et al., 2015; Gill, 2014).

The dimeric flavoprotein YieF converts hexavalent to trivalent Cr by transfer of four electrons in which three electrons are utilized for reduction of hexavalent Cr and last electron is shifted to oxygen. *Bacillus*, *Bifidobacterium*, *Lactobacillus* and *Streptococcus* are found in gut and mouth of human-beings which can bind and degrade hexavalent Cr. *Acinetobacter* species Cr1 strain can efficiently eliminate hexavalent Cr (Jeřábková et al., 2018; Rehman et al., 2020). The adsorption is the most efficient, economical and sustainable approach for elimination of hexavalent Cr from industrial effluent. Various sorbents such as activated carbon, bentonite, zeolite, agricultural wastes such as rice straw, peanut shell, sugarcane bagasse, fruit peel showed hexavalent Cr adsorption from contaminated effluent released from industries (GracePavithra et al., 2019; Junaid et al., 2016). Utilization of nanomaterials for elimination of chromium from polluted soil and water is recognized as a novel method because of small size of particles, wide surface area and stability (Ugwu and Agunwamba, 2020). Therefore, identification of more hyperaccumulator plant species and searching for new biostimulants are needed to remediate such large polluted agricultural land areas.

## 8. Conclusion and thoughts

This review emphasized the biogeochemistry of Cr in soil-plant environment system. The mobility, adsorption/desorption, phyto-uptake, compartmentation, toxicity and detoxification of Cr differ significantly with its chemical speciation. Cr adversely affects morphological and biochemical attributes of plants like transport of nutrients, enzymatic activities, photosynthesis and overall maturation and development. Cr resistant varieties and mutation of targeted genes can be selected to check the phytotoxicity and reduce the productivity of economically significant crops. The present review highlights adverse impact of CR on animals and humans, which need immediate action.

Various methods such as photocatalytic degeneration, adsorption, electrochemical, membrane, microbial techniques have been applied to bring Cr level below the critical values or guidelines set by various countries. The comprehensive analysis of the available literature reveals that most of the studies have been conducted are limited to laboratory scale and smaller number of studies have investigated the treatment of Cr contaminated sites. Based on the data summarized in this review article, the following research gaps need to be explored:

- There are very less number of plant species capable of hyperaccumulating Cr in their shoot tissues. More plant species need to be explored for Cr hyperaccumulation.
- Cr is well-known to cause toxicity to plants directly or indirectly by producing ROS, which impede with plant metabolism. However, the mechanisms of

actions behind these harmful effects of Cr in plants are still not well-known.

- The detoxification role of organic ligands such as phytochelatins, methionine, glutathione, proteins, vitamins and amino acids is not fully elucidated.
- Cr shows hormetic effect in plants, but the mechanisms as well as the optimal, essential and toxic values of Cr in soil are not well-established for its different chemical forms as well as for different plant species and soil types.
- There exist very low data regarding Cr-induced human health risks via consumption of Cr-contaminated food.

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