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Review Article

Chromium as an Environmental Pollutant: Insights on Induced Plant Toxicity

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In the past decades the increased use of chromium (Cr) in several anthropogenic activities and consequent contamination of soil and water have become an increasing concern. Cr exists in several oxidation states but the most stable and common forms are Cr(0), Cr(III) and Cr(VI) species. Cr toxicity in plants depends on its valence state. Cr(VI) as being highly mobile is toxic, while Cr(III) as less mobile is less toxic. Cr is taken up by plants through carriers of essential ions such as sulphate. Cr uptake, translocation, and accumulation depend on its speciation, which also conditions its toxicity to plants. Symptoms of Cr toxicity in plants are diverse and include decrease of seed germination, reduction of growth, decrease of yield, inhibition of enzymatic activities, impairment of photosynthesis, nutrient and oxidative imbalances, and mutagenesis.

1. Introduction

Chromium (Cr) is the 17th most abundant element in the Earth's mantle [1]. It occurs naturally as chromite ($FeCr_2O_4$) in ultramafic and serpentine rocks or complexed with other metals like crocoite ($PbCrO_4$), bentorite $Ca_6(Cr,Al)_2(SO_4)_3$ and tarapacaite (K_2CrO_4), vauquelinite ($CuPb_2CrO_4PO_4OH$), among others [2]. Cr is widely used in industry as plating, alloying, tanning of animal hides, inhibition of water corrosion, textile dyes and mordants, pigments, ceramic glazes, refractory bricks, and pressure-treated lumber [1]. Due to this wide anthropogenic use of Cr, the consequent environmental contamination increased and has become an increasing concern in the last years [3].

Chromium exists in several oxidation states, but the most stable and common forms are Cr(0), the trivalent Cr(III), and the hexavalent Cr(VI) species. Cr(0) is the metallic form, produced in industry and is a solid with high fusion point usually used for the manufacturing of steel and other alloys. Cr(VI) in the forms of chromate ($CrO_4{}^{2-}$), dichromate ($CrO_4{}^{2-}$), and CrO_3 is considered the most toxic forms of chromium, as it presents high oxidizing potential, high solubility, and mobility across the membranes in living organisms and in the environment. Cr(III) in the forms of oxides, hydroxides, and sulphates is less toxic as it is relatively insoluble in water, presents lower mobility, and is mainly bound to organic matter in soil and aquatic environments. Moreover, Cr(III) forms tend to form hydroxide precipitates with Fe at typical ground water pH values. At high concentrations of oxygen or Mn oxides, Cr(III) can be oxidized to Cr(VI) [4, 5].

As Cr(VI) and Cr(III) present different chemical, toxicological, and epidemiological characteristics, they are differently regulated by EPA, which constitutes a unique characteristic of Cr among the toxic metals [6]. Cr(VI) is a powerful epithelial irritant and also considered a human carcinogen [7]. Cr(VI) is also toxic to many plants [8] aquatic animals [9], and microorganisms [10]. Contrarily to Cr(VI), Cr(III) is considered a micronutrient in humans, being necessary for sugar and lipid metabolism [11] and is generally not harmful. In plants, particularly crops, Cr at low concentrations (0.05–1 $mg\,L^{-1}$) was found to promote growth and increase yield, but it is not considered essential to plants [5, 12]. In this context, accumulation of chromium in edible plants may represent a potential hazard to animals and humans.

2. Chromium in the Environment

2.1. Chromium in Water. Chromium may enter the natural waters by weathering of Cr-containing rocks, direct discharge from industrial operations, leaching of soils, among others. In the aquatic environment Cr may suffer reduction, oxidation, sorption, desorption, dissolution, and precipitation [6].

The aqueous solubility of Cr(III) is a function of the pH of the water. Under neutral to basic pH, Cr(III) will precipitate and conversely under acidic pH it will tend to solubilize. The forms of Cr(VI) chromate and dichromate are extremely soluble under all pH conditions, but they can precipitate with divalent cations [6]. The recommended limits for Cr concentration in water are 8 $\mu g\,L^{-1}$ for Cr(III) and 1 $\mu g\,L^{-1}$ for Cr(VI). In the effluents in the vicinity of Cr industries the levels of Cr range from 2 to 5 $g\,L^{-1}$ [13].

2.2. Chromium in Soil. The concentration of Cr in the soils may vary considerably according to the natural composition of rocks and sediments that compose them [6]. The levels of chromium in the soil may increase mainly through anthropogenic deposition, as for example atmospheric deposition [14], also dumping of chromium-bearing liquids and solid wastes as chromium byproducts, ferrochromium slag, or chromium plating baths [6]. Generally, Cr in soil represents a combination of both Cr(III) and (VI). As in aquatic environment, once in the soil or sediment, Cr undergoes a variety of transformations, such as oxidation, reduction, sorption, precipitation, and dissolution [6]. The oxidants present in the soil (e.g., dissolved oxygen and MnO_2) can oxidize Cr(III) to Cr(VI) [15]; however, it seems that oxidation of Cr(III) by dissolved O_2 is residual when compared with MnO_2. The forms of Cr(VI) are on the other hand reduced by iron, vanadium, sulphydes, and organic materials [16]. However, when the reducing capacity of the soil is overcome, Cr(VI) may persist in the soil or sediment for years, especially if the soils are sandy or present low levels of organic matter.

López-Luna et al. [17] compared the toxicity of Cr(VI), Cr(III), and Cr tannery sludge respecting to Cr mobility in the soil and toxicity in wheat, oat, and sorghum plants and found that Cr(VI) was more mobile in soil and caused higher toxicity on those plant seedlings, while tannery sludge was the least toxic [17].

3. Chromium in Plants

3.1. Chromium Uptake. The pathway of Cr uptake in plants is not yet clearly elucidated. However, being a nonessential element, Cr does not have any specific mechanism for its uptake and is also dependent on Cr speciation. Plant uptake of Cr(III) is a passive process, that is, no energy expenditure is required by the plant [3, 18]. The uptake of Cr(VI) is thought to be an active mechanism performed by carriers for the uptake of essential elements such as sulphate [19, 20]. Cr also competes with Fe, S, and P for carrier binding [8].

Cr(VI) has higher solubility and thus bioavailability is more toxic at lower concentrations than Cr(III), which tends to form stable complexes in the soil [17]. There are conflicting results concerning the uptake and translocation of Cr(VI). While some authors defend that Cr(VI) is reduced to Cr(III) on the root surface [21, 22], others suggest that dissolved Cr(VI) is taken up by plants without reduction [23].

Thus, Cr toxicity is dependent on metal speciation, which is determinant for its uptake, translocation, accumulation. Cr is toxic for agronomic plants at about 0.5 to 5.0 $mgm\,L^{-1}$ in nutrient solution and 5 to 100 $mg\,g^{-1}$ in soil [24]. Under normal conditions, concentration of Cr in plants is less than 1 $\mu g\,g^{-1}$ [25].

3.2. Chromium Accumulation and Translocation. Cr accumulates mainly in roots and shoots; however roots accumulate the major part, being usually only a small part translocated to the shoots [12, 26]. In pea plants exposed to Cr there was an increase in concentration of Cr in different parts of the plant with the increase of Cr supply. Accumulation of Cr in the different parts of the plant was in the following order roots > stem > leaves > seed [27]. Corroborating these results are the findings of several works and for instance, Huffman and Allaway [28] found that bean seeds accumulated about 0.1% Cr, while roots accumulated 98%. Furthermore, Liu and coworkers [29] studied hydroponically grown *A. viridis* L. under different concentrations of Cr(VI) and found that Cr was accumulated primarily in roots [29]. Another study performed by Vernay et al. [30] in *Lolium perenne* grown in the presence of 500 μM of Cr(VI) showed that roots accumulated 10 times more Cr than leaves. Spinach (*Spinacia oleracea* L. cv. "Banarasi") grown in the presence of Cr(VI) showed more accumulation of Cr in the roots than in leaves and stem showed the least accumulation [31]. Also, in celery seedlings grown in the presence of C(III) most Cr was accumulated in roots [32].

López-Luna and coworkers [17] found that roots of wheat, oat, and sorghum accumulated more Cr than shoots; however in spite of that, wheat, oat, and sorghum showed Cr translocation from roots to shoots. Furthermore, Zayed et al. [33] tested Cr(III) and Cr(VI) translocation in several crops and found that translocation of both Cr forms from roots to shoots was very low and accumulation of Cr by roots was 100-fold higher than in shoots, despite of the Cr species. However, Skeffington and coworkers [18] found that more 51Cr was transported from root to shoot when Cr(VI), rather than Cr(III), was supplied to the plant. At high Cr doses (1 mM $CrCl_3$) roots accumulated very high levels of Cr and translocation was mainly to cotyledonary leaves and only small amounts in hypocotyls. Chatterjee and Chatterjee [34] also found low levels of translocation of Cr from roots to the shoots in cauliflower (*Brassica oleracea*) grown on sand with 0.5 mM Cr(III).

These results may conclude that Cr is mainly accumulated in roots, followed by stems and leaves; however only small amounts of Cr are translocated to leaves. This pattern seems independent of the form of Cr tested.

3.3. Plants with Potential of Phytoremediation of Chromium Contamination. In phytoremediation, hyperaccumulator plants are used to extract and transform toxic metals, as Cr, into nontoxic and immobile compounds [35]. Cr hyperaccumulator plants can accumulate >1,000 $mg\,Cr\,kg^{-1}$ (DW), in plant leaves. These plants can tolerate metals through chelation with appropriate high-affinity ligands, biotransformation with reductants, and compartmentalization in the cytoplasm or in the vacuole. Thus, Cr immobilization in vacuoles in plant root cells may represent an important mechanism of Cr detoxification by the plant [8, 36].

The bioconcentration factor (BCF) and translocation factor (TF) are usually used to evaluate plant ability to tolerate and accumulate heavy metals. The BCF is the ratio of metal concentration in the plant tissue to the soil and TF is the ratio of metal concentration in plant shoots to the roots. Plants exhibiting a shoot BCF > 1 are suitable for phytoextraction, and plants with a root BCF > 1 and TF < 1 have the potential for phytostabilization [37].

Rafati and coworkers [37] evaluated the ability to uptake Cr from the soil by different organs of *Populous alba* and *Morus alba*. Leaves accumulated higher levels of Cr than stems or roots. However, neither *P. alba* nor *M. alba* showed potential of Cr phytostabilization, since presented TF > 1 and root BCF < 1; also these plants are not suitable for phytoextraction as they presented a BCF < 1. In another study, Gafoori and coworkers [38] evaluated the potential accumulation of heavy metals, including Cr in *Dyera costulata.* This specie presented high potential to retain high amounts of Cr in leaves, suggesting that this specie has high phytoremediation potential, as presented high translocation factor and low BCF factor. *Pluchea indica* also shown a good potential of phytoremediation, as it presented high levels of Cr accumulation and translocation to the leaves [39]. Mellem and coworkers [40] found that *Amaranthus dubius* tolerate high Cr(VI) concentrations as indicated by the BCF value > 2, showing good potential for phytoremediation. Furthermore, Gardea-Torresdey and coworkers [41] found that *Convolvulus arvensis* L. exposed to 20 mg L^{-1} of Cr(VI) demonstrated capability to accumulate more than 3800 mg of Cr kg^{-1} dw tissue, showing that this specie can be used in phytoremediation of Cr(VI) contaminated soils. Also, the concentration of Cr in leaf tissue (2100 mg kg^{-1} dw) indicates that this plant species could be considered as a potential Cr-hyperaccumulator.

Ipomoea aquatica is a chromium hyperaccumulator that shows no toxicity symptoms when exposed to high levels of Cr(VI). Up to 28 mg L^{-1} Cr(VI), *I. aquatica* exhibits uniform absorption characteristics showing over 75% removal of added Cr(VI). Over 90% Cr(VI) is accumulated in stems and leaves, that is, aerial regions [42]. Furthermore, Mant and coworkers [43] found that *Pennisetum purpureum* and *Brachiaria decumbens* exposed to 20 mg L^{-1} of Cr(III) showed a metal removal efficiency of 78% and 66%. Also, Barbosa and coworkers [44] found that *Genipa americana* has potential for Cr(III) phytoremediation in contaminated watersheds, since its seedlings uptake elevated amounts of Cr(III) from the solution and it presented high capacity of immobilizing and storing the metal on their roots.

3.4. Growth and Development

3.4.1. Germination. The presence of Cr in the medium may compromise several processes in plants, as for instance plant germination. Thus, the ability to germinate in the presence of Cr may indicate the degree of tolerance to Cr [45]. Oat seed germination was severely diminished (84%, resp. to the control) in tannery sludge soil with 4000 mg Cr kg^{-1}, while in tannery sludge soil containing 8000 mg Cr kg^{-1} both oat and sorghum seed germination was suppressed [17]. When comparing the sensitivity of sorghum, wheat, and oat germination to Cr, López-Luna and coworkers found that germination of sorghum and wheat were markedly affected at 500–1000 mg Cr(III) kg^{-1} soil respectively, while oat germination was not affected in levels of Cr(III) below 4000 mg kg^{-1} soil [17]. With respect to to Cr(VI) it affected wheat and sorghum germination at the maximum concentration of 500 mg kg^{-1} soil [17]. Germination of *T. aestivum* seeds was also affected by exposure to 100 mg L^{-1} of Cr(VI) [46]. *Echinochloa colona* (L.) seeds showed lower rates of germination when exposed to contaminated medium from chromite minewaste dumps [47]. The effect of Cr contamination on the germination medium was also tested in mungbean (*Vigna radiate* L.) tolerant/sensitive cultivars and results showed that in sensitive plants, germination rate decreased in plants exposed to 96 or 192 μM Cr(VI), while in tolerant plants germination was not affected [48]. Maize seeds exposed to Cr(VI) also presented decreased rates of germination when exposed to concentrations of 100–300 mg L^{-1} of Cr(VI) [49]. Zeid [50] found that germination of beans (*Phaseolus vulgaris*) was reduced in the presence of 5×10^{-2} M Cr(III). Similar results were found by Peralta et al. [45] in alfalfa seeds exposed to Cr(VI). In another study Scoccianti and coworkers [32] found that Cr(III) at concentrations of 0.01 to 10 mM inhibited germination of celery seeds; indeed at 10 mM a total inhibition was detected.

In spite of the findings above, Corradi et al. [51] suggested that Cr(VI) treatment may not affect seed germination, but instead inhibit radicles growth when they emerge and contact Cr solution. Nevertheless, decrease in germination is a common response upon exposure to heavy metals, such as Cd, Pb, and Hg [52–54]. This response of low levels of germination upon Cr exposure can be related with decrease in α and β amylase activities under Cr stress [50]. Amylase hydrolysis of starch is essential for sugar supply to developing embryos. Decrease in amylase activity under Cr treatment decreases sugar availability to developing embryo which may contribute to inhibition of seed germination [46].

3.4.2. Root Growth. Besides germination, also root growth is frequently affected by heavy metals. Peralta and coworkers [45] showed that 5 mg L^{-1} of Cr(VI) increased root growth comparatively to the control, and at higher doses (20 and 40 mg L^{-1}) there was a dose-inhibition effect. Cr(VI) in concentrations up to 200 mg L^{-1} decreased growth of paddy (*Oriza sativa* L.) [26]. Sensitive mungbean cultivars also showed decreased root growth when exposed to Cr(VI) [55]. Samantary [48] found that there was no root elongation in mungbean exposed to Cr(VI) concentrations between 96 and 1928 μM, but in lower concentrations, sensitive cultivars showed root elongation similar to the control. Also, development of lateral roots and root number was also affected by Cr exposure [48]. Moreover, roots of *Zea mays* L. treated with Cr(VI) were shorter and brownish and presented less number of roots hairs [56]. López-Luna et al. [17] found that root growth of oat and sorghum was decreased by Cr concentrations in the soil of 100 mg Cr(VI) kg^{-1} soil [17]. Decrease in root growth in presence of Cr(VI) can be explained by inhibition of root cell division and/or elongation, which might have occurred as a result of tissue collapse and consequent incapacity of the roots to absorb water and nutrients from the medium [57] combined with extension of cell cycle [26]. Reduced root surface in Cr(VI) stressed plants may contribute to decreased capacity of plants to search for water in the soil contributing to water stress. Despite of these results, stimulation of growth under low concentrations of chromium was also described (e.g., [58]). For example, Peralta et al. [45] found that roots of alfalfa plants exposed to 5 mg L^{-1} of Cr(VI) grew 166% more than the controls.

3.4.3. Stem Growth. Stem growth is another parameter usually affected by Cr exposure. Mallick and coworkers [56] found that shoot length of *Zea mays* L. decreased significantly at 9 μg mL^{-1} Cr(VI) after 7 days. Also, Rout and coworkers [47] found reduction of plant height and shoot growth due to Cr exposure in sensitive mungbean plants. In *T. aestivum* L. seedlings exposed to 100 mg L^{-1} of Cr(VI) for 7 days, Dey and coworkers [46] found decrease in root length by 63% and in shoot length by 44%, comparatively to the control. Concentrations of Cr(VI) in soil of 500 mg kg^{-1} also affected shoot growth of wheat and oat [17]. This decrease in plant height could be due to the reduced root growth and consequent decreased nutrients and water transport to the higher parts of the plant. Moreover, Cr transport to the aerial part of the plant can directly impact cellular metabolism of shoots contributing to the reduction in plant height.

3.4.4. Leaf Growth. Cauliflower grown on sand with 0.5 mM Cr(III) showed suppression of growth and leaves were smaller, chlorotic, and wilted comparatively to the control [34]. Leaf area is also usually decreased in response to increase of Cr concentration [53, 59]. Reduction of leaf area can be a consequence of reduction of the number of cells in the leaves stunted by salinization or reduction in cell size [60]. Watermelon plants growing in the presence of Cr(VI) showed reduced number and size of leaves and turned yellow, wilted, and due to loss of turgor hung down from petioles [61]. With continued Cr supply the lamina of affected old leaves became necrotic, permanently wilted, dry, and shed [61].

3.4.5. Yield. Plant yield is dependent on leaf growth, leaf area, and number. As Cr affects most of the biochemical and physiological process in plants, productivity and yield are also affected. Cr(VI) in irrigation water decreased significantly grain weight and yield (kg ha^{-1}) of paddy (*Oriza sativa*) up to 80% under 200 mg L^{-1} of Cr [26].

3.5. Physiological Processes

3.5.1. Photosynthesis. As other heavy metals, Cr may affect plant photosynthesis leading to decrease in productivity and ultimately to death. In a recent work, Rodriguez and coworkers [62] showed that exposure to Cr(VI) induced a reduction of both chloroplast autofluorescence and volume in pea plants. Moreover, both Cr(III) and Cr(VI) can cause ultrastructural changes in the chloroplasts leading to inhibition of photosynthesis [63].

Respecting to pigments, Samantary [48] found chlorophyll degradation in mungbean sensitive cultivars exposed to Cr(VI) and decrease in chlorophyll a and chlorophyll b contents. Furthermore, pea plants grown in sand under different concentrations of Cr(VI) presented reduced chlorophyll contents in leaves [27]. Dey and coworkers [46] also found that total chlorophyll content decreased in shoots of *T. aestivum* L. with increasing Cr(VI) concentration. Concerning Cr(III), Chatterjee and Chatterjee found a decrease in chlorophyll contents in cauliflower grown on sand with 0.5 mM of Cr(III) [34]. Also, in celery seedlings, Cr(III) reduced chlorophyll contents mostly at concentrations of 1 mM [64].

When comparing the effects of Cr(III) and Cr(VI) on photosynthesis parameters of water hyacinth, Paiva and coworkers [12] found that Cr(III) was much less toxic than Cr(VI), and might eventually increase photosynthesis and chlorophyll content. In another study, Zeid [50] found that low and moderate concentrations of Cr(III) (10^{-6} and 10^{-4} M) in irrigation solution increased pigment content in leaves, but higher Cr(III) concentrations (10^{-2} M) reduced the contents of chlorophyll a, chlorophyll b, and carotenoids.

This general profile of decrease in chlorophyll content at high Cr concentrations suggests that chlorophyll synthesis and/or chlorophyllase activity is being affected. Vajpayee and coworkers [65] showed that Cr affects pigment biosynthesis by, for instance, degrading δ-aminolaevulinic acid dehydrates, an essential enzyme in chlorophyll biosynthesis. Vernay and coworkers [30] also presented evidence that Cr competes with Mg and Fe for assimilation and transport to leaves, affecting therefore pigment biosynthesis. As the levels of reactive oxygen species (ROS) usually increase as a result of Cr exposure (e.g., [63, 66]), Juarez and coworkers [67] showed that ROS damages pigment-protein complexes located in thylakoid membranes followed by pheophitinization of chlorophylls (substitution of Mg^{2+} by H^+ ions) and destruction of thylakoid membranes.

Considering the effects of Cr on plant fluorescence parameters, Liu and coworkers [29] found that *A. viridis* L. exposure to Cr(VI) resulted in decreased net photosynthetic rate, transpiration rate, stomatal conductance, and intercellular CO_2 concentration. Also, chlorophyll fluorescence parameters F_v/F_m, F'_v/F'_m, ΦPSII, and q_p, decreased in Cr(VI)-treated, but q_N and NPQ showed an increase in Cr(VI)-treated plants [29], indicating that the photochemical apparatus might have been compromised. In another study, Vernay and coworkers [30] found that Cr(VI) affected *L. perenne* fluorescence parameters associated with PSII. In another study, these authors compared the effects of Cr(VI) and Cr(III) on *Datura innoxia* and found that Cr(VI) had a more toxic effect on those plants than Cr(III) [68]. In plants stressed with Cr(VI), a decrease in the quantum yield of PSII electron transport (ΦPSII), F'_v/F'_m and q_p was observed [68]. ΦPSII represents the number of electrons transported across a PSII reaction center per mole of quantum absorbed by PSII, F'_v/F'_m represents the excitation capture efficiency of open PSII reaction centers, while (q_p) reflects the number of open reaction centers and it is an indicator of the capacity of photochemical processes [69].

3.5.2. Mineral Nutrition. Cr, being structurally similar to other essential elements, may affect plant mineral nutrition. Mallick et al. [56] found that Cr exposure decreased Cu absorption in *Zea mays* roots, while leaves were not affected. Uptake of both macronutrients (e.g., N, P, K) and micronutrients decreased with increase of Cr(VI) in irrigation of paddy [26]. Also, decreased uptake of the micronutrients Mn, Fe, Cu, and Zn was detected by Liu et al. [29] in *A. viridis* L. exposed to Cr(VI). High content of Cr may displace the nutrients from physiological binding sites and consequently decrease uptake and translocation of essential elements. In watermelon plants grown in the presence of Cr, an increase in concentrations of P and Mn and decrease in Fe, Cu, Zn, and S contents in leaves was observed [61]. In *L. perenne,* Vernay and coworkers [30] found that Cr(VI) exposure affected mineral contents mostly Fe, Ca, and Mg. Cr(VI) also decreased Fe concentration in spinach [31] and sunflower [70]. The decrease in Fe concentration in leaf tissue in response to Cr toxicity is suggestive of Cr(VI) interference in the availability of Fe, leading to impairment of Fe metabolism [71].

3.5.3. Enzymes and Other Compounds. The activity of antioxidant enzymes, namely, peroxidase, catalase (CAT), glucose-6-phosphate dehydrogenase and superoxide dismutase (SOD) increased in case of Cr-sensitive of mungbean exposed to different Cr concentrations. However, the level of antioxidant enzymes decreased in Cr-tolerant cultivars [48]. SOD and CAT activities decreased in *T. aestivum* L. grown in the presence of $K_2Cr_2O_7$ in roots and shoots [46]. CAT activity also decreased in *A. viridis* L. exposed to Cr(VI) but an increase in SOD and guaiacol peroxidase (POX) activity was observed with increase of Cr(VI) concentration [29]. POX decreased in roots and increased in shoots of *T. aestivum* exposed to Cr(VI) [46]. Prado et al. [72] evaluated the metabolic responses to Cr(VI) exposure in floating and submerged leaves of *Salvinia minima* plants and found that Cr affected sucrose contents which were higher in Cr-treated leaves, while glucose contents showed an inverse pattern. Invertase activity also was also affected and suffered a decrease in floating leaves [72]. Zaimoglu and coworkers [73] studied the antioxidant responses of *Brassica juncea* and *Brassica oleracea* to soils enriched with Cr(VI) and found that total enzymatic activity was higher in *B. oleracea* than in *B. juncea.* Cr(VI) and also a decrease in CAT activity in both species [73]. Cellular antioxidants play an important role in protecting *Brassica* sp. to Cr-induced oxidative stress. This high activity of antioxidant enzymes and consequent detoxification of ROS contributes to relative tolerance of these species to Cr(VI). Furthermore, Guédard and coworkers [74] found that leaf fatty acid composition of *Lactuca serriola* was affected by the presence of Cr in metallurgic landfill soil.

3.6. Genotoxicity. Zou and coworkers [58] evaluated the effects of Cr(VI) on root cell growth and division of root tips of *A. viridis* L. and found that the mitotic index decreased with increased concentration of Cr(VI). Furthermore, Cr(VI) also affected chromosome morphology with increase in the frequency of c-mitosis, chromosome bridges, anaphase bridges, and chromosome stickiness [58].

Pea plants grown in the presence of Cr(VI) showed significant variations on cell cycle dynamics and ploidy level in leaves; however roots presented a cell cycle arrest at G2/M phase of the cell cycle; also polyploidization at both 2C and 4C levels was detected [75]. Moreover, in leaves and roots, an increase in DNA damage, assessed both by comet assay, and an increase in full peak coefficient of variation (FPCV) of G0/G1 were also detected [75]. Labra et al. [76] found hypermethylation of DNA and increase in DNA polymorphism in *Brassica napus* in response to Cr(VI) exposure. Cr(VI) also induced genotoxicity detected by AFLP analysis in *Arabidopsis thaliana* (L.) [77]. Furthermore, Knasmüller and coworkers [78] compared Cr(VI) and Cr(III) with respect to their ability to induce micronucleus in *Tradescantia* and found that only in Cr(VI)-exposed plants there was an increases in micronucleus frequencies. Moreover, Wang [79] in a survey to assess the genotoxic effects of Cr in water extracted from contaminated soil found that it was able to induce micronuclei in *Vicia faba* roots. Furthermore, Vannini and coworkers [80] evaluated the molecular changes induced by Cr(III) and Cr(VI) on germination kiwifruit pollen and concluded that neither Cr species induced a genotoxic effects. Both Cr species induced a strong reduction of proteins involved in mitochondrial oxidative phosphorylation and a decline in ATP levels [80].

4. Concluding Remarks

This paper includes an overview of the literature about Cr toxicity in the environment, especially in water and soil and provides new insights about Cr toxicity in plants. Cr exists mainly in three oxidative states Cr(0), Cr(III), and Cr(VI), which are the most stable forms of Cr. As Cr(0) is the metallic form, the forms of Cr(III) and Cr(VI) are the most preponderant in soils and water. Once in water/soil, Cr suffers a variety of transformations such as oxidation, reduction, sorption, desorption, precipitation, and dissolution. While Cr(III) solubility is dependent on pH, Cr(VI) is extremely soluble under all pH conditions. Cr as being a nonessential element for plants does not have any specific mechanism for its uptake. Cr(III) uptake is a passive process, whereas Cr(VI) uptake is performed by carriers of essential elements such as sulphate. Cr accumulates mainly on plant roots, being translocated to shoots in small levels, independently of Cr specie. Despite known toxicity of Cr to plants, there are several plants that hyperaccumulate this metal contributing to its removal from soil/water, showing good potential for application in Cr phytoremediation strategies. Cr affects several processes in plants, namely, seed germination, growth, yield and also physiological processes as photosynthesis impairment and nutrient and oxidative imbalances. Also, it has been shown that Cr is able to induce genotoxicity in several plant species.

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