Chapter 14
Effects and Responses of Chromium on Plants

Shipa Rani Dey, Monika Sharma, and Prasann Kumar

Abstract There are many ways that chromium is used in industry has resulted in its status as a serious environmental pollutant in the modern world. It is of recent concern that soil and water may be contaminated with chromium (Cr) due to its presence in the environment. When it comes to the toxicity of chromium, the level of toxicity is determined by the valence state of the element. In contrast to the valence state Cr(6+), which is very toxic and highly mobile, the valence state Cr(3+) is much less toxic and much less mobile. Chromium does not have a specific transport mechanism that enables it to be transported from plant to plant in a specialized manner. As a result, this element is taken up by plant components that are responsible for transporting essential ions throughout the plant. Chromium can have a toxic effect on the growth and development of plants by causing changes in the germination process. This is in addition to alterations in the growth of stems, roots, leaves, and other plant parts. Also, it is worth mentioning that these alterations may occur due to the toxic effects that Cr has on the growth and development of plants. In the physiological realm, it has been demonstrated that the presence of Cr in soil has a detrimental impact on the physiological processes that plants engage in, including photosynthesis, mineral nutrition, and the relationship between water and soil. As well as having the capacity to generate reactive oxygen species, plants have also been found to display a direct effect of Cr exposure on enzymes and other metabolites, which in turn can cause oxidative stress in plants, as a consequence of being exposed to Chromium. Because of their potential for bioremediation, the utilization of plants for the bioremediation of Chromium contamination that can accumulate or stabilise Chromium compounds has recently achieved a great deal of attention. This is due to the plants' potential for bioremediation.

Keywords Abiotic · Bioremediation · Chromium · Toxic · Mitigation · Physiological · Photosynthetic · Zero hunger · No poverty

S. R. Dey · M. Sharma · P. Kumar (✉)
Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab 144411, India
e-mail: prasann0659@gmail.com

N. Kumar et al. (eds.), *Chromium in Plants and Environment*, Environmental Science and Engineering, https://doi.org/10.1007/978-3-031-44029-8_14

14.1 Introduction

Chromium is found in a wide range of minerals and rocks due to its high reactivity. It is also found in freshwater, as it is easily soluble in water and can be taken up by aquatic organisms. It is also found in soil and sediment, as it is part of the Earth's crust and cycles through the environment. The two forms of chromium least prone to going through chemical changes are hexavalent chromium (also known as Cr-VI) and trivalent chromium (Cr-III) (Prasad et al. 2021). Hexavalent chromium is more prevalent in industrial areas due to its increased use as a corrosion inhibitor in metalworking and welding. Trivalent chromium is more prevalent in natural environments, as it is released from the weathering of rocks and minerals. It can also be found in certain foods, such as grains, fruits and vegetables, due to its uptake by crops. Hexavalent chromium has a strong oxidizing nature, which makes it a compound that can cause cancer and mutations in living organisms. Therefore, it is important for those living in industrial areas to be aware of the possible risks of hexavalent chromium exposure. Several nations have designated Cr as a high-priority pollutant, including the United States Environmental Protection Agency (USEPA) (Mushtaq et al. 2021). To ensure the safety of residents in these areas, it is important to understand the levels of hexavalent chromium that are present and to take necessary precautions to protect against its known harmful effects. It is thought that chromium's toxicity is due to its ability to pass through the intercellular membranes and produce intracellular Reactive Oxygen Species (ROS), which are extra-toxic. Therefore, it is essential to monitor the levels of hexavalent chromium in the environment and to take proactive measures to protect against its potential health risks. A thousand times more dangerous and one hundred times more mutagenic than Cr(3+), Cr(6+) is one hundred times more toxic than Cr(3+). This makes Cr(6+) a dangerous contaminant that must be monitored and managed to avoid potential health risks. Trivalent chromium, on the other hand, has been found to play an important role in the regulation of glucose, triglycerides, and cholesterol in humans. However, despite its potential health benefits, Cr(3+) must still be monitored and managed due to its toxicity, as even small amounts can cause serious health risks. Despite this, a higher concentration of Cr(3+) can inhibit the activity of metalloenzymes due to its ability to form complexes with organic compounds (Zhitkovich et al. 2001). Therefore, it is important to ensure that the concentration of Cr(3+) is carefully regulated to provide potential health benefits while avoiding its associated health risks. In soil, groundwater, and sediments, it ranks 2nd after arsenic (Kar et al. 2008; Ogundiran and Afolabi 2008). With this in mind, it is essential to maintain the concentration of Cr(3+) at optimal levels, to enable its desirable health benefits while avoiding the associated health risks. In the periodic table, Cr belongs to group VI-b (Mandich 1997). The oxidation state of chromium ranges from -2 to $+6$. Consequently, knowledge of the oxidation state of chromium is critical in determining the risk of exposure and the health implications associated with it. Smith et al. (2002) refer to chromium (6+) and chromium (3+) as the most significant oxidation states of Cr. Additionally, chromium (3+) is considered more toxic than chromium (6+), thus it is important to differentiate between

the two-oxidation states for accurate assessment. The following is an excerpt from Shanker et al. (2005), which suggest that it is the element Cr which plays a greater role in plant growth than the other metals, but that this element overall is considered to be of lesser importance in the context of plant development. Furthermore, while chromium (6+) is typically considered less toxic than chromium (3+), it is important to take into account the element's oxidation state when evaluating its impact on plant growth. Evidence suggests that, although the element Cr has a positive effect on plant development, it is not as influential as other essential metals. The amount of elemental Cr that was released into the environment each year ranged from 2,000 to 3,200 tonnes in some Asian countries (Chandra et al.1997). According to Krishnamurthy and Wilkens, the groundwater and soil of those countries were found to contain a very high amount of Cr contamination, including 14,800 mg/l in groundwater and 25,900 mg/l in soil. This contamination was highly concerning, and urgent action was needed to reduce the amount of Cr released into the environment. It has become increasingly apparent that the accumulation of Cr in the soil is one of the most pressing environmental concerns on a global scale, because of its detrimental effects on both crop production and human health (Tiwari et al. 2009). Consequently, immediate attention must be given to developing strategies to reduce the amount of Cr released into the environment. The toxicity of Chromium to plants has been demonstrated by demonstrating the failure of plants to grow, the formation of chlorosis in the leaves, and the damage to the roots, as well as a decrease in grain yield (Scoccianti et al. 2006; Ali et al. 2013a). To minimize the impacts of Cr on the environment, it is essential to focus on interventions that prevent Cr from entering the soil, such as washing off industrial waste, ensuring proper disposal of hazardous waste, and monitoring activities that may increase Cr concentrations. Furthermore, plants that grow in places where there is a lot of chromium are more likely to produce reactive oxygen species (ROS) as a result of the presence of chromium, such as H_2O_2, OH^-, and O_2. Additionally, Cr-resistant species may be used to reduce the levels of ROS in contaminated soil, thus providing a further safeguard against the environmental impacts of Cr. These reactive oxygen species have been recognized for their detrimental effects on the production of biomolecules and their ability to cause damage, as well as damage to membranes and electrolyte leakage (Ali et al. 2011, 2015a, b). To this end, the use of Cr-resistant species may provide an effective strategy to mitigate the potential environmental damage caused by ROS. Malondialdehyde, also known as MDA, is one of the final products of the peroxidation process. It is created when free radicals cause damage to lipids through the process of peroxidation, which results in the production of malondialdehyde. Therefore, the use of Cr-resistant species may offer a promising solution to reduce MDA levels and consequentially, the peroxidation of lipids. Aside from this, it also acts as a marker for the formation of free radicals and the resulting damage to the tissue those results from their presence, so it also acts as a warning indicator. Additionally, MDA can also be used as an indicator of the effectiveness of dietary antioxidants, as its levels will be inversely proportional to the number of free radicals present. In the process of seed germination, chromium can cause metabolic disorders because of its presence. In this way, MDA is an essential marker for monitoring the damage caused by free

radicals, as well as an indicator of the effectiveness of antioxidants and the potential damage chromium can cause in the process of seed germination. As a result, it interferes with the process by which stored food is converted into energy to assist in the subsequent successful emergence and establishment of seedlings in the environment by interfering with the processes involving the transformation of food into energy. This disruption of energy production results in a decrease in stored energy reserves, thereby reducing the potential for successful seedling emergence and establishment. In a study conducted on cowpea seeds (Vigna sinensis (L.), Savi ex Hassk) containing various concentrations of Cr^{6+}. It has been demonstrated that a significant decrease in both the amylase activity in the seeds, as well as the total amount of sugar in the seeds, resulted from the exposure to $Cr^{6+.}$ Which in turn resulted in a depressing effect on germination characteristics (Nath et al. 2008). This suggests that Cr^{6+} had a negative impact on the germination process, leading to reduced seed viability. There was a correlation found between higher levels of chromium in its various valence states and a concurrent decrease in seed germination, as reported by Nagajyoti et al. (2010). The researchers studying the effects of a variety of trace metals on three distinct species of Veronica (Plantaginaceae), the researchers found a significant positive correlation between both the concentrations of iron and Chromium in the plant tissues (Zivkovic et al. 2012). Numerous studies have been conducted on the toxicity of Chromium in crop plants. The metabolism of plants, like maize (Zea mays) (Sharma and Pant 1994), barley (Hordeum vulgare) (Ali et al. 2004; Sharma et al. 1995a, b), and sorghum, is significantly impacted by chromium. For example, Riaz et al. discovered that the growth, yield, and biochemical parameters of chickpea (Cicer arietinum var NM-88) plants were severely inhibited when concentrations of the chromium salts $CrCl_3$ and K_2CrO_4 were at a level of 300 g/mL. This was the case even when the plants were grown under optimal conditions. Additionally, significant amounts of chromium were found in the roots at a concentration of 1.912 mg Cr/g of dry mass; however, even lower concentrations were also transferred into the shoots (0.086 mg Cr/g of dry mass) and the leaves (0.074 mg Cr/g of dry mass). Despite being used at a low concentration of 1.0 mM (Sharma et al. 1995a, b), the researchers reported that not a single seed could be produced at a concentration of this concentration. This illustrates the extremely low and ineffective efficiency of chromium in the plant's metabolism, making it clear that at such a low concentration, it fails to induce the necessary conditions for proper seed production. This concentration did not produce any viable seed, indicating that chromium could be toxic to the reproductive capacity of plants, even at relatively low concentrations.

14.2 Environment Concentrations and Sources of Chromium in the Air, Water, and Soil

The majority of chromium found in crustal rocks is derived from industrial sources, although naturally occurring chromium can also be found in crustal rocks. This is due to anthropogenic activities such as mining, smelting, and other industrial processes, as well as natural weathering and erosion processes. There are several different forms of ferrochrome ($Fe_2Cr_2O_4$) that are found in nature; the most common is ferrochrome ($Fe_2Cr_2O_4$) found in the earth's crust as well as other minerals. These ferrochrome deposits often contain high concentrations of chromium, making them attractive targets for extraction and use in industrial applications. Among the most significant environmental pollutants are the ones that are caused by human activity, specifically industrial processes that use chrome as a component of their components (primarily leather tanning, textile dyeing, textile pigment production, metallurgy, organic synthesis, cleaning agents, wood processing, anodizing aluminium, catalytic manufacture, alloy preparation, Cr plating, and wood preservation) (Alloway 2013). Chromium is released into the environment through emissions from these processes, and it can have a negative impact on air and water quality and can cause health issues for humans and animals. Sixty to seventy per cent of the world's total production of marketable chromite ore, which comes to a gross weight of 24,000_103 metric tonnes, is used up in the production of stainless steel and other alloys. The tanning of leather, electroplating, the production of pigments, and other chemical industrial processes use greater than 15% of the total energy (Papp and Lipin 2010). Currently, more than 4000 tanneries around the world participate in chrome tanning methods. In addition, chromite ore is also used for refractories, heaters, and bricks for the metal industry, further increasing the need for its production. Because of the tannery industry in India, an estimated 2,000–3,000 tonnes of elemental chromium are released into the environment every year because of pollution. Consequently, the effects of chromium pollution on the environment and human health have been a growing concern, with exposure to hazardous levels of chromium being linked to serious health conditions. The tanning agent chrome (Cr) is used in approximately 80–90% of the leather industry. The effluents from these tanneries contain approximately forty per cent of the Cr that is used in the form of Cr(6+) and Cr(3+) salts (Sundaramoorthy et al. 2010). As far as chromium concentrations are, concerned, freshwater concentrations of chromium can be as high as 0.1–0.5 mg/l, while salt water concentrations of chromium can be as low as 0.0016–0.05 mg/l (Kumar and Puri 2012). However, due to the high levels of chrome used in the tanning process, the effluent produced can cause environmental damage if not handled properly. The World Health Organization (WHO) suggests that the maximum possible limits for the discharge of Cr(6+) into inland surface water and drinking water should be 0.1 mg/l and 0.05 mg/l, respectively. There are a number of chemical concentrations that are expected to be permitted and these numbers refer to the maximum concentrations. Therefore, it is important to adhere to these maximum possible limits to ensure the safety and quality of drinking water and inland surface water. These are

the maximum permissible limits. According to F€orstner and Wittmann (2012), Cr holds the position of the 21st most abundant element that can be found in the crust of the earth. A study by Polti et al. (2011) has shown that the amount of chromium in the soil can fluctuate between five and three thousand mg per gram, depending on the soil characteristics (Polti et al. 2011). Even though the amount of chromium in soil fluctuates, the maximum permissible limits for its concentration should be observed to ensure safety and health. There are many sources of chromium in addition to natural rocks, including solid wastes, industrial effluents, ferrochromium slag with chromium-based byproducts, leachates, and dust particles with concentrations of chromium that are significantly higher than those allowed in permissible limits. Moreover, such human activities can cause an exponential increase in the concentrations of Chromium in the environment, which can be a major cause of concern.

14.3 Chromium's Toxic Effects on Plants

The compounds that are made up of chromium are extremely toxic to plants and if they meet them, then their growth and development can be slowed or stopped. In addition, the compounds can act as a poison to animals that ingest them, leading to potentially severe health risks. The use of chrome compounds should be avoided at all costs. Therefore, the potential environmental and health risks associated with chrome compounds make them dangerous and should be avoided. In spite of the fact that certain crops are not affected by low levels of Chromium (3.8 10 4 AMS) (Huffman and Allaway 1973a, b), Chromium is toxic at a dry weight of 100 AMS per kg for the majority of higher plants (Davies et al. 2002). Consequently, it is important to be aware of the associated risks and take all necessary precautions to avoid the use of chrome compounds whenever possible. When chromium levels reach a certain threshold level, the element is no longer a necessary component of life and therefore toxic. Therefore, it is essential to take all the appropriate steps to limit exposure to chromium-based toxins, as their presence in the environment can be hazardous to our health. A plant's metabolism cannot be effected by the metal, which does not have any function within an ecosystem, even if it could play a role in the metabolic processes of a plant (Dixit et al. 2002). As such, it is important to ensure that chromium levels are strictly monitored, as any excess of the element can lead to hazardous levels of contamination and can have a detrimental effect on the environment. A plant's accumulation of Chromium can have a number of detrimental effects, including the loss of pigment content, stunted growth, the induction of chlorosis in young plants, ultrastructural modifications to the chloroplasts and cell membranes, mutated enzyme functions, and impairment of root cells. Chaudhury and Panda (2005) indicate that Chromium accumulates in plants in a negative way. As a result, it is important to ensure that the level of Chromium in soil is monitored to ensure that plants are not exposed to excessive levels of this element. Because of its toxicity, chromium can stop seeds from germinating and slow the development of radicles in plants as well

as prevent seeds from germinating (Panda et al. 2002). Therefore, it is essential to closely monitor Chromium levels in soil to mitigate the potential impacts it can have on plant growth. Plants are susceptible to a variety of factors that can lead to a reduction in their size, including a reduction in their rate of cell division, which occurs because of the induction of chromosomal aberrations (Liu et al. 1993). To ensure optimum plant growth, it is critical to keep track of Chromium levels in order to reduce the chances of chromosomal aberrations. According to Yoon et al. (2006), there is a variation in the accumulation of metals in different species of plants, and they attribute this difference to the variation in the genetic code of the plants. To further reduce the chances of chromosomal abnormalities, it is important to use strategies to monitor and manage Chromium levels accurately, as this will ensure the highest potential for successful plant growth. Physiological and morphological traits of genotypes can be used as an indicator of genetic variation in a population (Ishikawa et al. 2006). To this end, it is imperative to monitor genetic variability in plants with physiological and morphological traits; this will provide valuable insight into maximizing potential growth (Ishikawa et al. 2006). It is important to understand that when the concentration of Chromium is in the micromole range, plant cells can exhibit severe symptoms of phytotoxicity. This knowledge is essential to assess the effect of Chromium on plant cells and to determine the threshold concentration of Chromium that is safe for the plants to grow in their optimal potential. A plant such as Lemna minor, Pistia sp., and Taxithelium nepalense have their unique taxonomy, particularly in terms of their ability to alter ultrastructure at the chloroplast level, which ultimately ends up inhibiting photosynthesis (Choudhury and Panda 2005). Furthermore, this understanding is key to improving our comprehension of how plants process and metabolize Chromium, allowing us to assess its full potential to be a beneficial component of soil health. There is evidence that higher concentrations of Cr can negatively affect the roots of plants, causing them to wilt and leading to plasmolysis in the root cells (McGrath 1995). However, it is important to note that a careful balance of Cr must be maintained in soil, as too much can be detrimental to the health of plants. The results of the study showed that hexavalent Chromium has the potential to cause severe phytotoxic effects at high concentrations (1 mM), such as the distortion of the chloroplast membrane and the severe disarrangement of the thylakoids at high concentrations (1 mM). Additionally, it was observed that the accumulation of Cr in the roots of plants significantly decreased at higher concentrations, indicating that the plants were unable to absorb the metal effectively. This suggests that as the concentration of Cr increases, the metal becomes increasingly toxic and can lead to reduced growth and development of the plant. Because thylakoids become seriously disorganized, these effects occur because of these conditions. As a result, plants are particularly sensitive to the presence of high concentrations of Cr, as it can greatly disrupt their growth and development. It has been shown that aquatic plants, such as Vallisneria spiralis, can store substantial quantities of chromium in their tissues, which results in a reduction for biomass of these plants (Vajpayee et al. 1999, 2000, 2001). This confirms that Cr is a critical factor in the growth and health of plants and that it is important to keep Cr levels within healthy limits. Because Chromium is capable of degrading aminolevulinic acid dehydratase, an enzyme that

plays a significant role in the production of chlorophyll, it has a negative impact on the utilization of aminolevulinic acid. Therefore, managing Chromium levels is essential in order to ensure optimal plant growth and health. Carotenoids in plants are susceptible to being degraded when Cr is present (Rai et al. 1992). In solution culture, Cr is more dangerous. After all, it is in a soluble form, it is very simple for plants to take up. In soil, most of the Cr is no longer available because of adsorption, reduction, and precipitation (Zayed and Terry 2003). In the following sections, we will investigate several of the metabolic and physiological methods that are altered in plants due to the presence of Chromium. These changes can be observed in a variety of metabolic pathways and physiological processes.

14.4 Plant Chromium Uptake, Transport, and Distribution

In spite of the fact that we are still learning about the mechanisms involved in the absorption of Cr and the distribution of this nutrient throughout the plant's vegetative and reproductive parts, we still lack a comprehensive understanding of what causes this process. To gain a better insight into how this process works, further research is needed to explore the various mechanisms and pathways associated with Cr absorption and distribution. As Cr is not a vital element for the survival of plants, plants do not have specific mechanisms for it to be absorbed into their tissues through their roots. However, despite this, plants may still be able to accumulate Cr if it is available in the soil solution, allowing for a passive absorption process. Due to this, the carriers that are used during the uptake of heavy metals also serve as carriers during the uptake of heavy metals. Consequently, the effectiveness of Cr uptake by plants depends on its availability in the soil solution and its association with the soil carriers. Plants absorb Cr from the soil and carry it throughout their tissues in a manner that changes with time depending on the mechanism that they use to do so. Therefore, understanding the mechanism of Cr uptake by plants is critical for determining how much of it is available for use in the environment. The uptake process appears to be influenced by both active and passive transports; the former is more prevalent at lower concentrations, whereas the latter becomes more significant once the levels of the compound reach toxic levels (when membrane selectivity is lost). Moreover, proton-dependent transporters and anion channels facilitate the active uptake of Cr by plants, while passive transport mainly takes place through an anion-exchange mechanism. It is important to note that the effects of Cr contamination on plant physiology are determined by the metal speciation, which is responsible for the uptake, mobilisation, translocation and accumulation of chromium within the plant system, all of which contribute to the plant's vulnerability to harm. Therefore, it is essential to consider the chemical form of Cr in order to accurately assess its potential impacts on the plants. Several active mechanisms constitute the pathway for the transport of Cr(6+) that consists of ion transporters such as sulphate, one of the most important ion transporters (Cervantes et al. 2001). Consequently, understanding the chemical form of Cr is critical in order to accurately evaluate its effects on the plants.

Additionally, numerous active mechanisms facilitate the pathway of Cr(6+) through ion transporters, including sulphate, which is the most widely used ion transporter (Cervantes et al. 2001). As far as carrier binding goes, it is established that the metals chromium, iron, sulfur, and phosphorus are highly competitive for carrier binding with one another. Furthermore, these mechanisms enable Cr(6+) to bind to several other ions, such as iron, sulfur, and phosphorus, leading to intense competition for carrier binding. In order to establish tolerance to toxic metals by plants, it is believed that the plasma membrane of the root, which is the first functional structure to meet toxic metals, plays a very important role in the process by which these metals are tolerated by plants. Consequently, the plasma membrane is thought to possess special mechanisms that enable plants to effectively respond to and tolerate the presence of toxic metals in the soil. There was a reduction in the uptake of Cr(6+) with the use of metabolic inhibitors but there was no adverse effect on the uptake of Cr(3+) with the use of metabolic inhibitors. This suggests that plants have evolved specific mechanisms for dealing with different forms of chromium, allowing them to better survive in soils containing toxic metals. It is evident that the amount of metabolic energy available for the uptake of Cr(6+) is determined by the amount of energy available for the uptake of Cr(3+), but not the amount of energy available for the uptake of Cr(6+). This means that plants have developed ways to prioritize the uptake of Cr(3+) over Cr(6+) as Cr(3+) is less toxic than Cr(6+). They have also evolved ways to efficiently use the energy they have available to take up the less toxic form of chromium, allowing them to survive in soils with a higher concentration of toxic metals. According to Barcelo and Poshenrieder (1997), there are two types of uptake of Cr(3+): a non-active process, which is thought to occur in a passive manner, and an active process, which occurs in a more active manner. By actively taking up the less toxic form of chromium, the organism's survival rates are significantly increased, even in environments that are more toxic. Skeffington et al. found that the sulphate carrier is less effective at taking in Cr(VI), while Cr(3+) forms binuclear complexes by affixing itself firmly to the carboxyl group of amino acids found in proteins. It has been observed that the cells immediately convert Cr(6+) that has been taken into Cr(3+) after it has been taken in. In the interior of the cell, Cr(3+) can be found in the cytosol. Because of its low mobility and recalcitrant nature, chromium can remain in the soil for an extended period, which can the amount of the element that is absorbed by plants should be increased. Because root exudates contain organic acids, which can combine with chromium to form complexes, and, as a result, making chromium available for uptake by the root may be a significant factor in the increased accumulation of chromium in the root. According to Srivastava et al. (1999a, b), a higher rate of chromium absorption in the plant's roots of *Lycopercicum esculentum* could be attributed, in part, to the root contains carboxylic acid in addition to the amino acids that it also contains. The xylem of plants is where most of the movement of Cr takes place. The distribution of Cr within crops possessed a consistent quality that was independent of the characteristics of the soil, as well as the concentration of this component. The roots have always contained the highest quantity of the contaminant element, while the vegetative and reproductive organs have always contained the lowest quantities (Pulford et al. 2001). In the case of beans, the seeds were only

found to contain 0.1% of the Chromium that had accumulated, while the roots were found to contain 98% of it (Huffman and Allaway 1973a, b). Chromium gets stuck in the vacuoles of the root cells, which makes it less toxic. The higher amount of Cr in the roots of plants could be a natural way for the plant to deal with the element's toxicity and limit its exposure to it (Shanker et al. 2004). Because Cr(6+) and Cr(3+) must travel through the endodermis via the symplast. Cr(6+) in cells can likely be readily reduced to Cr(3+). The retention of Cr(3+) in the root cortex cells in the presence of low concentrations of Cr(6+) is one of the factors that contribute to the decreased toxicity of Cr(3+). Even though Cr(6+) reducing enzymes have not been found in higher vascular plants, they have been found in many different types of bacteria and fungi (Cervantes et al. 2001). The amount of chromium that accumulated in *Vigna radiata* was relatively low, and as a result, only a trace amount was found in the shoot. In contrast, Vigna unguiculata showed the highest amount of chromium accumulation. In most plant species, According to Shanker et al. (2005), the chromium that is transported from the roots to the shoots occurs at a very slow rate as it moves from the roots to the shoots. However, Vigna unguiculata had significantly higher chromium accumulation than other species, demonstrating its ability to transport chromium from the roots to the shoots more quickly than other species. The level of chromium accumulation in the roots of both of these species of Vigna was significantly greater when compared to the accumulation in the stems of the plants. There is a possibility that the majority of the chromium is stored in the vacuoles of the root cells to render it non-toxic. There may be a reason for the poor translocation of chromium from the soil to the shoot due to this reason. This suggests that vacuolar sequestration of chromium in root cells may be an important mechanism to reduce its toxicity and limit translocation to the shoot. Possibly, this might be a way for the plant to protect itself from its natural toxicity by protecting itself in this way. Therefore, it is likely that the root of the plant is employing a protective strategy to limit the accumulation of chromium in other parts of the plant. Therefore, it can be concluded that Vigna species can accumulate chromium in their roots, primarily to reduce its toxicity and protect the plant from potential harm.

14.4.1 Growth and Development

Plant growth and development are essential for the continuation of life and the spread of species. Without these processes, our planet would be unable to sustain itself and many plants and animals would become extinct. To ensure the continuation of life, we must protect and foster healthy plant growth and development. Due to the ongoing nature of their activity, and the fact that they rely heavily on the resources found in the soil and air around them to survive, they can sustain themselves. Therefore, it is important to monitor and manage these processes to ensure the viability of our planet's ecosystems. Consequently, plants play an integral role in our global ecosystem, providing food, shelter, and oxygen while stabilizing temperatures and maintaining biodiversity. As such, it is necessary to protect and preserve our plant

resources to safeguard the health of our environment. A major factor that contributes to the expression of growth is the genotype. This is both a function of the genotype and the environment, which includes both internal and external growth factors. Accordingly, it is essential to understand the genotype and its interplay with the environment to effectively conserve and protect our plant resources. Moreover, this knowledge can inform and support strategies to promote the health and sustainability of our global ecosystem. As a function of both the genotype and the environment, growth is primarily determined by both. Therefore, it is important to gain a comprehensive understanding of the genotype and its relationship with the environment to successfully preserve and safeguard our plant resources. Moreover, this information can be utilized to inform and facilitate the implementation of strategies that promote the wellbeing and durability of the entire planet. Ultimately, the growth of species is determined by both the genetic makeup and environmental conditions. There is a change in the sequence of plant growth and development in response to the presence of Chromium in the environment in which the plant is growing, which causes changes in the plant's growth and development. Chromium plays a significant role in altering the growth trajectory of plants, as it affects the genetic expression and environmental factors in tandem.

14.4.2 Germination of Seeds and Development of Seedlings

To understand how chromium affects physiological processes, one of the first things you need to know is that chromium affects the initial stages of the germination process in seeds. If a seed can germinate in an environment that already contains chromium, that means that that seed has a high tolerance for the presence of this metal (Peralta et al. 2001). According to Rout and Almeida, it took 200 AM Cr order to achieve a 25% reduction in the rate of seed germination in the weed Echinochloa colona. A study conducted in 1982 found that Phaseolus vulgaris exhibited a 48% lower germination rate when presented with high levels of hexavalent chromium (500 ppm) in the soil in comparison to a control plant when exposed to low levels (50 ppm) of hexavalent chromium. As a result of exposure to 40 parts per million of Cr(6+) in a contaminated medium, the seeds of lucerne (Medicago sativa cv. Malone) proved to be less able to germinate and grow in an uncontaminated medium. These findings were published in 2001 by Peralta et al. (2001). This reduction was by 23%. There was a reduction in sugarcane bud germination of between 32 and 57% when 20 and 80 ppm of Cr were used, respectively (Jain et al. 2000). It has been speculated that the decreased germination of seeds due to chromium stress may be caused by the inhibitory effect of chromium on the interaction of amylases and the subsequent transport of sugars to the embryo axes when chromium is present (Zeid 2001). Alternatively, the increased protease activity that occurs as a result of the chromium treatment may also be a factor that may be responsible for the diminished germination of the Cr-treated seeds (Zeid 2001), as it probably increases the enzyme activity of the seed during the treatment process.

14.4.3 Root Growth

Heavy metals present in plants and crops have the effect of slowing down the rate at which roots grow. As a result, crops can be adversely affected, potentially leading to lower yields and reduced quality. It has been shown that this effect is observed in both trees and crops (Tang et al. 2001). To combat this, farmers must consider methods to reduce or remove heavy metals from the soil to maximize the health and productivity of their crops. It has been reported that Prasad et al. (2001) found that cadmium, chromium, and lead were the metals that caused the greatest damage to the new root primordia in Salix viminalis. To further reduce the harmful effects of heavy metals on crops, farmers must consider methods such as land application of compost, phytoremediation, and the use of nanoparticles to reduce soil concentrations of these pollutants. In contrast to the other heavy metals that were investigated in this study, Chromium caused significantly greater damage to the root length than any other heavy metal that was examined. To further mitigate the effects of Chromium, farmers must explore more effective strategies than the previously mentioned methods, such as the use of biochar or chemical binding agents. The Caesalpinia pulcherrima is one of the most significant arid-adapted trees, and its roots and dry weight were inhibited when a concentration of 100 ppm Cr was applied to it (Iqbal et al. 2001). However, it is yet to be established whether Caesalpinia pulcherrima could be a viable option for farmers dealing with Chromium contamination, and further research is needed to assess this potential. In the soil, when 20 mg of Cr(6+) kg^{-1} of $K_2Cr_2O_7$ were present as $K_2Cr_2O_7$ in the soil, both the total root weight of the wheat and the root length of the wheat were adversely affected. To explore the viability of Caesalpinia pulcherrima as a potential solution, further research is needed to understand how it may respond to, and counteract, the effects of Chromium contamination. The research conducted by Panda and Patra (2000) revealed that the presence of chromium caused a significant increase in the root length of seedlings when they were grown in the presence of nitrogen (N) nutrition levels resulting in the presence of chromium. To gain a better understanding of the viability of Caesalpinia pulcherrima, further research is needed to determine how it responds to, and combats, chromium contamination, beyond what was observed in the study of Panda and Patra (2000). As a result of increased concentrations of Chromium present in all of the nitrogen treatments, however, the roots grew shorter with increased concentrations of Chromium present. Moreover, additional analysis must be conducted to determine if Caesalpinia pulcherrima is capable of sustaining chromium pollution in the long-term, as the observed root growth inhibition suggests that it may not be a sustainable solution for long-term chromium contamination. It is interesting to note that Samantaray et al. (1999) conducted a study involving five different cultivars of mung bean and found that when the soil contaminated with chromite mine spoiled for 28 days after root emergence, root growth was severely affected. Furthermore, the root biomass of each cultivar was significantly reduced, suggesting the potential of mung bean as an indicator species for soil contamination. As part of our research with chromite mine spoil soil, we made the following observation during the course of our experiments. We observed

that the root growth of each cultivar was severely stunted and the root biomass of each cultivar decreased as the contamination period increased. This finding highlights the potential of mung bean as a suitable indicator species for soil contamination. As revealed by studies conducted with a scanning electron microscope on roots that had been exposed to Cr, there was an increase in the number of root hairs that formed as well as an increase in the thickness of the pith and the cortical layers when compared with roots that had not been exposed to Cr (Suseela et al. 2002). This finding is indicative of mung bean's ability to adapt to soil contamination and absorb Cr, making it a promising indicator species for research. This could be due to the inhibition of root cell division or elongation or an extension of the root cycle in the roots as a result of chromium toxicity, causing the general response of decreased root growth. Furthermore, this adaptation could also be attributed to the plant's ability to form chelates and bind the Cr, preventing its accumulation in the root cells. Both of these possibilities are possible. When seedling roots come into direct contact with Cr in the medium, the roots collapse. Consequently, when high concentrations of both chromium species are present in combination, the roots cannot take up water from the medium, which is a possible cause of a reduction in root growth when high concentrations of both chromium species are present in combination. Therefore, it is important to ensure that only one species of chromium is present in the medium to avoid these negative effects on root growth.

14.4.4 Stem Growth

Several reports have indicated that the presence of Cr can have a negative impact on the development of the plant's height and the growth of its shoots (Rout et al. 1997). When chromium was added to nutrient solutions in sand cultures of oats in concentrations of 2, 10, and 25 parts per million, Anderson et al. (1972) found that the plant height decreased by 11%, 22%, and 41%, respectively, when chromium was added to nutrient solutions at a concentration of 2, 10, and 25 parts per million. The results were compared to those of the control group. Researchers believe that the presence of Cr(6+) resulted in shorter plant heights for several species of Curcuma sativus, Lactuca sativa, and Panicum miliaceum mainly due to the presence of Cr(6+). They conducted research in 1995 to determine the effects of Cr(6+). During their study on lucerne cultures, according to the findings of Barton et al. (2000), they discovered that the incorporation of Cr(3+) into the soil reduced the rate at which the shoots grew. In a glasshouse experiment conducted by Sharma and Sharma, they found that Wheat cv. UP 2003 that had been sown in sand containing 0.5 AM sodium dichromate experienced a significant reduction in plant height 32 and 96 days after planting. When Cr was applied to Sinapsis alba soil at rates of 200 or 400 mg kg^{-1}, along with nitrogen, phosphorus, potassium, and sulphur fertilizers, there was a discernible drop in the overall height of the plant (Hanus and Tomas 1993). A reduction in root growth may be the primary cause of the decrease in plant height. As a consequence, there may be a reduction in the transport of nutrients and

water to the higher parts of the plant as a result. As such, the application of Cr may have negative impacts on plant growth and lead to an overall decrease in biomass. The movement of chromium from the part of the plant that is in the air to the part of the plant that is in the ground can also have a direct effect on the cellular metabolism of the leaves, which contributes to the shortening of the leaves. Furthermore, the decrease in leaf size could be caused by the lack of an adequate supply of chromium, which serves as a key nutrient for cell metabolism.

14.4.5 Leaf Growth

To determine the amount of crop harvest that is realized, the growth of the leaves, their expansion, and their total number all play a significant role in determining the amount of crop harvest that is achieved. The amount of Chromium that was added to the nutrient solution caused the number of leaves produced by each wheat plant to decrease by fifty per cent as result of the addition of Chromium. The results of a study conducted by Tripathi et al. (1999) showed that the leaf area and biomass of Albizia lebbek seedlings were significantly altered when exposed to a high concentration (200 ppm) of the contaminant Cr(6+). A study conducted by these scientists indicates that the characteristics of leaf growth could be used as bioindicators of contamination with heavy metals and to select species that are resistant to such contamination. Moreover, these findings demonstrate the importance of conducting studies which consider the impact of heavy metals on the growth characteristics of different species. It was observed that when bush bean plants were grown in a 1–10 Ag cm^3 Chromium medium, both the primary leaves as well as the trifoliate leaves lost a fair amount of leaf area. Furthermore, the results of this study highlight the need for further research which examines the effects of heavy metals on the growth of different plant species. Additionally, exposure to high concentrations of chromium can cause a significant reduction in leaf area. Compared to the primary leaves of the plants, the trifoliate leaves were more affected by the Chromium than the primary leaves. Therefore, it is clear that the degree of sensitivity to heavy metals varied between plant species and that the trifoliate leaves were more susceptible to Chromium than the primary leaves. When 100 ppm of Cr(6+) was introduced into the soil, researchers discovered that bush bean plants experienced a reduction in their dry leaf yield of up to 45%. The researchers Karunyal et al. (1994) conducted research to determine how tannery effluent affected the leaf area and biomass of the plant. A significant reduction was observed in the leaf area and leaf dry weight of Oryza sativa, Acacia holosericea, and Leucaena leucocephala regardless of the concentration of tannery effluent that was used for all three plants. The results of a study conducted by Singh (2001) which examines the effects of Cr(3+) and Cr(6+) on spinach, found that the application of Cr at levels of 60 mg kg^{-1} or higher resulted in burns on the tips or margins of the leaves, reduced leaf size, and slowed the growth rate of the leaves. A study conducted by Jain et al. (2000) found that leaves were affected by chlorosis when the Cr concentration in the leaves reached 40 ppm, whereas necrosis occurred at a Cr concentration of

80 ppm. According to the research conducted by Pedreno et al. (1997), using a range of heavy metals, it was found that chromium had the greatest impact on leaf growth in tomato plants and that this impact was greater on the younger leaves as opposed to the older leaves. Interestingly, Poschenrieder et al. (1993) found that a decrease in the amount of leaf biomass in P. vulgaris was correlated with an increase in the amount of chromium extractable from oxalate acid when leaf biomass decreased.

14.4.6 Total Dry Matter Production

The primary requirement for higher yields to be obtained from plants is the increase in the amount of dry matter produced by the biomass of the plants. It has been estimated that 80–90% of the dry matter produced by plants is composed of carbon compounds. Specifically, the presence of heavy metals and chromium stress in the environment is the basis for the accumulation of organic substances and the production of dry matter. According to Bishnoi et al. (1993a, b), the increase in the photosynthetic process and the increase in source size is what allowed the accumulation of organic substances and the production of dry matter. Vallisneria spiralis was the subject of a research project to investigate the effect of chromium accumulation and toxicity on biomass production. This was done as part of an investigation into the effects of chromium accumulation on biomass production. A significant negative impact was seen on the amount of dry matter that was produced as a result of the concentrations of Cr(6+) in the nutrient medium that was greater than 2.5 Ag ml^{-1} in the nutrient medium. According to Vajpayee et al. (2001), the purpose of the study was to determine the relationship between chromium accumulation and biomass production (Vajpayee et al. 2001). In a study conducted by Zurayk et al. (2001), it has been shown that the interaction between salinity and Cr(6+) reduced the amount of dry biomass accumulation caused by Portulaca oleracea. There was an interaction between these two factors that resulted in this outcome. When grown at a concentration of 0.5 mM Cr(6+), cauliflower of the cv. Maghi variety significantly reduced dry biomass (Chatterjee and Chatterjee 2000). The results of a study conducted by Kocik and Ilavsky (1994) on sunflower, maize, and Vicia faba indicated that the effect of chromium on the quality and quantity of biomass was not significantly affected by 200 mg kg^{-1} of Cr(6+). On the other hand, there was a positive correlation between the contents of the soil and the amount of chromium that was taken up by the plant tissue Kocik and Ilavsky's (1994). There was a discernible drop in the amount of dry biomass produced by S. alba during the flowering stage when Cr(VI) was added to the soil at rates of either 200 or 400 mg kg^{-1} in combination with N, P, K, and S fertilizers (Hanus and Tomas 1993). A higher dry weight (DW) of roots and leaves was observed in P. vulgaris and maize plants which had been exposed to 1 AM Cr(III) compared to control plants. This growth in DW was more noticeable in conditions where there was a shortage of Fe. It was shown that in the water cultured plants that were exposed to 10 ppm of Chromium, the dry weight of the whole plant was

reduced by a significant amount, going from 88.4 g plant^{-1} in the control group to 28.4 g plant^{-1} in the group exposed to 10 ppm of Chromium.

14.4.7 Yield

There is no doubt that Cr has an equivalently negative impact on the yield and productivity of the crops, and as a direct result, it has had a profoundly negative impact on the vast majority of physiological and biochemical methods. The study conducted by Golovatyj et al. (1999) found that when 100 or 300 mg kg^{-1} of Cr was added to the soil, the yields of barley and maize decreased. It was found that the number of flowers produced by each wheat plant decreased by 50% at 0.05 AM chromium compared to the control, while the decline was even greater at 0.5 AM chromium than at 0.05 AM chromium. There was a 59% decrease in the number of grains produced by each plant when the control was in 0.05 AM chromium as compared to the control. Even though the control grain had the highest grain DW, an increase in Cr level resulted in a reduction of 58–92% of the grain DW of the control grain. It has been shown that a higher concentration of Cr leads to a decrease in tillering and an increase in seed deformities. Sharma and Mehrotra, in a study published in 1993, found that the amount of dry seed per plant was 2.11 g in the absence of Cr, 0.39 g in the presence of 20 ppm of Cr, and 0.16 g in the presence of 200 ppm of Cr according to their study. As a result of the effects that chromium has on the processes that take place within a plant during its early stages of growth and development, it is eventually responsible for a significant decline in yield as well as the amount of total dry matter within a plant. The reason for this is that chromium impairs the production, translocation, and partitioning of assimilates to the plant's economic components as they are absorbed into the plant. As chromium has a direct effect on plants, there was almost a complete decrease in the yield of the plants as well as in the amount of dry matter produced as a result of its presence. This could ultimately result in a lack of nutrients in the shoot of the plant, as it makes it harder for the plant to absorb minerals and water, leading to slow growth and development of the plant. There was an increase in the amount of Cr(+6) that could enter the roots passively as the plants grew, and when Cr(6+) was transferred from the roots to the shoots, it damaged the plants' photosynthetic and mitochondrial systems, which in turn resulted in a lack of growth. Moreover, oxidative damage may have resulted in the breakdown of the normally functioning mechanism for the selective uptake of inorganic nutrients. In this way, the roots would have been able to absorb higher concentrations of Cr(6+) as a result of this. On the other hand, ligand substitution does not affect the rate at which Cr(3+) reacts with the ligand. Therefore, it can form substitution-inert metalloprotein complexes in living organisms as a result of this property, which is a unique property that reduces the role it plays in the production of toxic symptoms in living organisms. There is an opinion that the toxicity of Cr(III) can be attributed to indirect effects, such as the change in pH or the stopping of ions from moving around, which are examples of indirect effects.

14.5 Effect on Photosynthetic Pigments and Carbon Assimilation

There have been several studies that have shown that plants that have been exposed to Cr(6+) stress have been shown to have reduced amounts of total chlorophyll, chlorophyll a, chlorophyll b, and carotenoids (Vajpayee et al. 2000; Appenroth et al. 2003; Rai et al. 2004; Paiva et al. 2009; Redondo-Gómez et al. 2011). As a result of 72 h of exposure to 100 M Cr(6+), Rai et al. (2004) observed that Ocimum tenuiflorum lost approximately 70%, 69%, 73%, and 87% of its chlorophyll, chlorophyll a, and chlorophyll b content, respectively, following 72 h of exposure to 100 M Cr(6+). It was done as a reaction to the harmful effects of Cr(6+) on the body. It was found that Chl a exhibited a higher degree of sensitivity when exposed to Cr(6+) stress than Chl b (Vajpayee et al. 2000; Paiva et al. 2009). It was found that in P. amarus, Rai and Mehrotra (2008) discovered that chlorophyll b was much more sensitive to the effects of Cr(6+) stress than chlorophyll a. In other words, Pandey et al. (2005) found that after exposure to Cr(6+), the amounts of chlorophyll pigments in B juncea increased after a period of fifteen days in a Cr(6+) controlled experimental condition. As a result of the constrained expansion of the leaves, they attributed this increase proportionately to the increased growth rate. There have been studies that have shown that Cr(III) has detrimental effects on the net photosynthetic rate of G americana seedlings when grown in water that is contaminated with Cr(III). The stomatal conductance of H. annuus as well as the net photosynthesis of the plant were both inhibited by Cr(3+) when it was present at a concentration of 100 M in the plant (Davies et al. 2002). A study conducted by Paiva et al. (2009) on Eichhornia crassipes showed that both Cr(3+) and Cr(6+) significantly decreased leaf gas exchange, Chlorophyll fluorescence parameters, and photosynthetic pigment levels, with Cr(6+) being the most toxic of the two compounds. The effect of exposure to Cr(6+) has also been observed to have an inhibiting effect on chlorophyll fluorescence emission spectrum, a decrease in the chlorophyll a/b ratio, as well as a reduction in PSII activity in Z. mays. It has been shown that Cr(6+) toxicity induced stomachal closure, reduced net photosynthetic rates, and reduced transpiration in O. sativa (Ahmad et al. 2011), *A. viridis* (Liu et al. 2008), L. perennial (Vernay et al. 2007), and a Cr-sensitive cultivar of *V. radiata*. It was determined that these changes were caused by a decrease in the net photosynthetic rate (Samantaray 2002). It has been suggested that the decreased chlorophyll content that has been observed as a response to chromium exposure is a result of the impaired activity of various enzymes responsible for chlorophyll biosynthesis. Two examples of such enzymes are protochlorophyllide reductase and aminolevulinic acid dehydratase. ALAD is also known as porphobilinogen synthase. The production of chlorophyll in plants is dependent on the presence of these two enzymes (Ganesh et al. 2008). According to Vasjpayee et al. (2000), it has been shown that Cr(VI) reduced chlorophyll levels in *Nymphaea alba* at a concentration of less than one mM, inhibited ALAD activity, and increased the amount of-aminolevulinic acid (ALA) in Nymphaea alba (Nymphaea alba). When there is a high concentration of Cr in the environment, ALAD activity is inhibited, which may contribute to the use

of PBG (porphobilinogen) for the synthesis of chlorophyll that is limited in the presence of Cr toxicity. It has been suggested that the reduction of chlorophyll pigments that can be attributed to Cr(VI) stress may be connected to a reduction in the plant's ability to absorb magnesium and nitrogen, both of which are essential elements that are found in chlorophyll molecules. Additionally, magnesium and nitrogen deficiencies caused a precipitous drop in the amount of light that was absorbed from 500 to 2,600 nm as a result of a lack of magnesium and nitrogen. Upon the application of Cr, Sharma et al. (1995a, b) found that there was a significant reduction in the amount of Hill activity in T. aestivum (VI) under the influence of Cr. In addition to negatively affecting the assimilation of carbon dioxide, Cr(6+) also has a negative effect on negative photosynthetic rates (Vernay et al. 2007; Liu et al. 2008; Subrahmanyam 2008). In addition to obstructing the production of pigments that are involved in photosynthesis, the toxicity of Chromium causes a reduction in the amount of CO_2 that can be absorbed by plants as a result of a reduction in pigment production. The result of this is a decrease in the dry biomass of the plant. There is evidence to suggest that the detrimental effects of Cr can be traced back to its ability to cause changes in the activities of carbon fixation enzymes, as well as a disruption of Cr's effect on the electron transport chain of photosynthesis (Larcher 1995). As Joshi et al. (2003) demonstrated in a study on the leaves of Cyamopsis tetragonoloba, the activity of malate dehydrogenase and RuBP carboxylase in addition to the rate of photosynthesis were both inhibited by Cr(6+) when the concentration ranged from 2 to 6 parts per million. However, when the concentration of Cr(6+) was increased to 1 ppm, the opposite effect was observed concerning the observed effects. In response to the presence of Cr(6+), both Pueraria montana and Salvinia minima did not exhibit any discernible changes in their internal CO_2 concentrations. As a result, the amount of carbon that is readily available in the presence of Cr(6+) does not affect the amount of CO_2 that is uptaken (Nichols et al. 2000). Based on the results of Subrahmanyam (2008), it appears that the ratio of Fv/Fm in T. aestivum was not affected by Cr(VI) and that the photochemical processes occurring in PSII in T aestivum were not affected by Cr(VI). In contrast, it impeded the assimilation of CO_2 into the cells as demonstrated by the lower in vivo quantum yield of PSII, as well as a slower electron transport rate (Subrahmanyam 2008). In Salvinia natans plants exposed to Cr-rich wastewater, PSI and PSII activity increased, but the ratio of Fv to Fm did not change after they were exposed to Cr-rich wastewater. While RuBisCO (ribulose-1,5-biphosphate carboxylase–oxygenase) showed an increase in activity after the same exposure, RuBisCO activity decreased after the same exposure (Dhir et al. 2009). There has been evidence that Cr(VI) can cause a decrease in photochemical quenching while increasing non-photochemical quenching based on the work of Vernay et al. (2007), Liu et al. (2008), and Subrahmanyam (2008). In light of this, it can be assumed that ATP and NADPH levels have declined (Subrahmanyam 2008). Because plants have a diminished capacity for light absorption, this is evidence that Cr(6+) disturbs a mechanism that carries electrons during photosynthesis (Nichols et al. 2000). A study published by Dixit et al. (2002) suggests that Cr(6+) prevents uncoupled electron transport within a cell. It is suggested that Cr(6+) can be found to bind to many different sites along the electron transport chain in plants based on the

findings of this study. As a result of these researchers' findings, they have concluded that the change may have been caused by a redox change in copper and iron carriers. As a result of their research, they proposed that Cr(6+) could have been transferred through the cytochrome system in the mitochondria to reduce the concentration of Cr(6+) in the mitochondria. A possible explanation for this could be that the reduced heme group of cytochrome served as a site of Cr(6+) binding, thereby preventing electron transport (Dixit et al. 2002). Apart from its ability to bind to the complex IV of cytochrome oxidase, Cr(6+) has also been shown to bind to cytochrome a3, which in turn reduces the activities of both of these molecules to a significant extent (Dixit et al. 2002). Cr(6+) ions may have a negative impact on photosynthesis and the transfer of excitation energy because of the abnormalities and ultrastructural changes that are caused by Cr(6+) ions. These abnormalities include undeveloped lamellar systems, widely spaced thylakoids, as well as a decreased number of grana in the chloroplasts (Paiva et al. 2009). A study conducted by Juarez et al. (2008) suggests that the pheophitinization of chlorophylls and the destruction of pigment–protein complexes observed in thylakoid membranes may be both outcomes of the production of reactive oxygen species (ROS) in response to the stress induced by Cr(6+). As a result of research involving Cr(6+) and PSII, researchers found that Cr(6+) significantly impacts the PSII performance index. This can be accomplished by reducing the number of active reaction centres produced by absorption, the yield of primary photochemistry, and how efficiently a trapped exciton can move electrons into the electron transport chain (Appenroth et al. 2001). The efficiency of primary photochemistry, as well as the efficiency with which a trapped exciton can move an electron into the electron transport chain, are all factors that have been considered. Accordingly, one of the primary targets of chromium toxicity was the reduction in the number of active reaction centres, as well as damage to the oxygen-evolving complex (Appenroth et al. 2001). As a part of their studies, Bishnoi et al. (1993b) investigated the effects of Cr(6+) on PSI and PSII activity in isolated chloroplasts of P. sativum which were exposed to the presence or absence of Cr(6+). It was found that the presence of Cr(6+) had a greater effect on the activity of PSI than the absence of Cr(6+). As a result of this study, it was discovered that PSI and the light-harvesting complex of PSII were less sensitive to the presence of Cr(6+) than PSI and the basic complex of PSII, as well as the connecting antenna of PSII. Nevertheless, a different study has found that PSII has a greater sensitivity to Cr(6+) than PSI, which suggests that they are both sensitive to Cr(6+) (Appenroth et al. 2003).

14.6 Changing the Balance of Nutrients as a Result

When plants are put under stress from chromium, both the uptake of nutrients and their biomass are impacted to a greater degree. Chromium interferes with the absorption of vital nutrients in a complex manner. Several studies have shown that both Cr(3+) and Cr(6+) interact with the consumption of macronutrients such as N, P, K, and Mg. These studies were done by Turner and Rust (1971), Sela et al., Biddappa and

Bopaiah, Moral et al., and Davies et al. (2002). It has been demonstrated that Cr(III) inhibits the uptake of vital mineral elements and lowers the amount of calcium that is present in the cells. In *H. annuus*, the concentrations of N, P, and K were reduced by 100 μM of Cr(3+), while concentrations of aluminium, iron and zink were increased (Davies et al. 2002). According to the findings of Liu et al. (2008), when copper, iron, and zinc were present in the environment of A viridis, their uptake was inhibited by the presence of Cr(6+). Citrullus vulgaris was exposed to Cr(6+), which resulted in an increase in the accumulation of phosphorus and zinc and a decrease in sulphur and copper in the plant as a result of the exposure (Dube et al. 2003). As far as the effect of Cr(6+) on the uptake of Mn is concerned, there have been contradictory reports concerning the effect that it has on the uptake of Mn. In C. vulgaris (Dube et al. 2003) and L. perenne, an increase in the uptake of manganese was caused by Cr(6+) (Vernay et al. 2007), but it caused a decrease in the absorption of manganese in Brassica oleracea (Chatterjee and Chatterjee 2000) and Amaranthus viridis (Liu et al. 2008). The levels of nitrogen, phosphorus, and potassium in the leaves of *Oryza sativa* were lower when Cr(6+) was present at 50–500 mg kg^{-1} in the soil (Ahmad et al. 2011). It is well established that Cr(6+) competes with both iron and phosphorus for surface root sites and binding sites (Chatterjee and Chatterjee 2000). As a result of Cr(6+) interfering with the absorption of iron, there is a reduction in the accumulation of iron, which is necessary for the biosynthesis of chlorophyll and heme. Additionally, there was a decrease in the levels of activity of the heme enzymes found in S. oleracea, which suggests that there was interference in the iron metabolism (Gopal et al. 2009). According to Turner and Rust (1971), the decreased amount of biomass in G. max that occurs after exposure to Cr(6+) is thought to be caused by direct interference of Chromium in the process of phosphorous metabolism, as well as there, is a limit placed on the amount of sulphur that can be incorporated into certain essential amino acids. In their study, Sundaramoorthy et al. (2010) illustrated that the primary reason for the decrease to determine the effects of Cr(6+) toxicity on Oryza sativa L., the total dry weight of the root and shoot was determined was a decrease in water uptake as well as an expansion of root cells. As a way of comparison, Han et al. (2004) found that impaired metabolic processes were responsible for 57% of the high-shoot dry mass in B. juncea when the concentration of Cr was 500 M. These processes restrict the extracting compounds that have been stored in the cotyledon and are essential for the continued expansion and development of the plant. At a concentration of 2 M, Cr(6+) has been shown to stop the roots of Z. mays from taking in K^+ and H^+. This suggests that it interferes with the transport activities of plasma membranes. When S. kali was exposed to a concentration of chromium between 5 and 20 mg l^{-1}, it took in less K, P, Mg, and Cu through its roots and less Ca, Fe, and Cu through its leaves; Nevertheless, the effect was not consistent regardless of the Cr speciation. In general, the conditions of Cr(3+) led to a reduction in the number of macronutrients and microelements that were absorbed in comparison to the conditions of Cr(6+). According to Redondo-Gómez et al. (2011), the uptake of essential nutrients was inhibited in cordgrass, *Spartina argentinensis*, when Cr(III) concentrations of 1.5 mg g^{-1} were present. During the research that was conducted by Barcelo and Poschenrieder (1997), it was determined that Cr(6+) is absorbed

by higher plants through sulfate carriers, which are membrane transporters that are involved in the uptake of Cr(6+). According to Kleiman and Cogliatti (1997), after discovering an increase in Cr(6+) influx in sulfate-deprived T. aestivum plants, it is likely that sulfate plays a role in the transport of chromium in plants. The evidence suggests that the sulphate transporter (BjST1) is suppressed in roots of B juncea under Cr(6+) stress, resulting in reduced uptake of sulphate as well as a reduced expression of the sulphate transporter (BjST1). As a result, it can be concluded that sulphate carriers play a key role in Chromium transport. There is also evidence to suggest that the accumulation of Cr(6+) is greater in B juncea than in other species when the expression of the sulphate transporter (SHST1) is increased. The research study conducted by Kim et al. (2006) indicates that the uptake of Cr(6+) and the tolerance to Cr(6+) in transgenic tobacco are both controlled by an over expression of MSN1, a putative yeast transcriptional activator (Nicotiana tabacum).

14.7 Water Balance as a Result of the Effect

As discovered by Barcelo et al., the influence of Cr(6+) on water relations is dependent upon its concentration, and it also depends upon the type of leaves, which differs depending on the type of Cr(6+) applied. In primary leaves, the values of ψs and ψw were found to be lower at growth-inhibiting concentrations, while ψp was found to be higher. There was, however, a phenomenon in bifoliate leaves in which when the concentrations of all of the compounds did not have an inhibitory effect, w and p increased while s decreased, whereas trifoliate leaves, on the other hand, exhibited the opposite response. Gopal et al. (2009) illustrated that Cr(6+) lowers the physiological availability of water in S. oleracea leaves. There was a decrease in leaf water potential as well as an increase in diffusive resistance, both of which indicate that the plant is suffering from water stress.

14.8 Other Biochemical Effects

In addition, research has shown that the toxicity of Chromium harms the biochemical processes of plants in other ways. In the case of P. vulgaris, the occurrence of Cr(6+) stopped the production of ethylene from 1-aminocyclopropane-1-carboxylic acid made by the plant itself (ACC) (Poschenrieder et al. 1993). Even though Cr was responsible for the disintegration of the membrane that caused the inhibitory effect, the changes in metabolism that occurred as a result of Cr(6+) exposure were the cause of the inhibitory effect, as either inhibition of ACC synthase activity or the diversion of metabolic steps that occur before ACC-catalyzed reactions were to blame for this. These alterations were responsible for the inhibitory effect (Poschenrieder et al. 1993). It has been shown that Cr(6+) can disrupt the electron transport chain in mitochondria isolated from root cells of P. sativum, resulting in the chain's

inactivation at concentrations of 20 and 200 M (Dixit et al. 2002). As a result of the study, it was revealed that both NADH: cytochrome c oxidoreductase and succinate: cytochrome c oxidoreductase activities have been significantly inhibited by the inhibitor, respectively, with cytochrome oxidase being the enzyme most sensitive to the inhibitor (Dixit et al. 2002). Because of Cr(VI; 150 mg l^{-1}), the amount of IAA and IBA found in the roots and shoots of *T. aestivum* decreased, while the amount found in the seeds increased (Zhang et al. 2009). Exposure to Cr(6+) in P. sativum root plasma membrane vesicles resulted in an increase in the NADPH-dependent superoxide production as well as the activity of NADPH oxidase, which led to the discovery that Cr(6+) was responsible for these changes, while there was a noticeable drop in the amount of activity displayed by NADH ferricyanide oxidoreductase. It is speculated that these findings might lead to the conclusion that Cr(6+) may disrupt the normal functioning of plasma membranes as a result of its effects (Pandey et al. 2009). There has been recent research suggesting that the presence of chromium in the earth's crust of metallurgical landfills (at a concentration of 1,346 mg kg^{-1} soil) can affect the ratio of saturated to unsaturated fatty acids found in the Lactuca serriola leaf. It has been demonstrated in previous studies that Cr(6+) inhibits the activity of plasma membrane H^+-ATPase (Shanker et al. 2005) and Na^+/K^+-dependent ATPase, whereas Cr(III) inhibits the activity of Ca^{2+}-dependent ATPase.

14.9 The Uptake and Translocation of Cr in Plants

There has been a significant amount of attention being paid all over the world to the uptake of Chromium by plants and its translocation to different parts of the plant as of late. Recent developments have been the focus of this attention. In addition to the fact that Chromium plays such an important role in human metabolism, it also plays a role in the development of carcinogenic effects on humans. As Cr does not participate in the metabolic processes that take place within plants, the mechanism by which plants take up Cr has not yet been fully understood because it does not participate in these metabolic processes. It has been shown that root systems in plants are the primary sources for chromium uptake, which varies from one plant type to another, as well as the type of chromium speciation, which may be Cr(3+) or Cr(6+) (Smith et al. 2002). Additionally, there is also evidence to suggest that the uptake of Cr from aqueous media is dependent on the pH, the concentration, and the salinity of the medium in addition to the presence of dissolved salts in the medium (Chatterjee and Chatterjee 2000). A study by Kocik and Ilavsky found that the formation of complexes between Cr and organic ligands appears to facilitate increased uptake of Cr by plant tissues by facilitating the formation of these complexes. To take in Cr(III), plants use a mechanism known as diffusion, the process of which is a passive one that is carried out at the cation exchange site of the plant cell wall. In an energy-dependent active process, Cr(VI) is taken up by the cell via the phosphate and sulphate transporters, because of its structural similarity to phosphate and sulphate (Chandra et al. 1997). There is evidence that ferric reductase enzymes are involved in the immediate change

of Cr(VI)–Cr(III) in roots when Cr(VI) is transported by active transport (Biacs et al. 1995). The converted Cr(III) binds to the cell wall of the plant cells, thus preventing it from moving any further through the various tissues of the plant (Sharma and Mehrotra 1993). It has been shown that an increase in the expression of MSN1, a putative yeast transcriptional activator, in transgenic Nicotiana tabacum led to an increase in the tolerance and ability of the plant to absorb Cr and S (Smith et al. 2002). As a result of additional research carried out on N. tabacum, it was found that there was an increase in the expression of the gene for sulphate transporter one (NtST1) under the influence of Cr stress. The sulfate transporter seems to take up both S and Cr, which indicates that they are both taken up by the transporter. The ABC transporter is generally considered to be the mechanism used by prokaryotic organisms to transport sulphate from one place to another (Paiva et al. 2009). It has been discovered that there are some different sulphate transporters in eukaryotes that have varying degrees of affinity for the substrates in their environment. The plasma membrane of Chlamydomonas reinhardtii has been found to contain six different sulphate transporters and all of these sulphate transporters belong to the Na^+/SO_4^{2-} and H^+/SO_4^{2-} transporter families. A hypothesis has been put forth that these transporters may play a role in regulating the movement of Cr within plants (Redondo-Gómez et al. 2011). Chromium is the least mobile heavy metal among all the heavy metals found in plant roots among all the heavy metals. According to some studies conducted up to this point, the roots of plants contain the highest concentration of chromium when compared with other parts of the plant such as the leaves and stems (Smith et al. 2002). Earlier studies conducted by Zayed et al., for example, revealed that the formation of insoluble Cr compounds in roots led to an accumulation of chromium that was over a hundred times higher than that found in vegetable shoots as a result of the insoluble Cr compounds. Similarly, it was discovered that *P. sativum* and *S. oleracea* L. cv. Banarasi accumulated a greater quantity of Cr in their roots than in their leaves and stems. Notably, under conditions of Cr toxicity, bean plants accumulated 98% of the element in their roots, but only 0.1% of it was found in their seeds (Rai et al. 2004). When 0.50 mM of Cr(VI) was applied to Lolium perenne as part of another study, the results showed that there was a 10 times higher accumulation of Cr in the plant's roots than in its leaves. The cytoplasm and intracellular spaces of the rhizome of Iris pseudacorus were found to contain higher concentrations of Cr than those found in the root cell wall and the cytoplasm of Iris pseudacorus (Barcelo and Poshenrieder 1997). When compared to the shoots, the accumulation of Cr was greater in the plants' roots of *T. aestivum*, *A. sativa*, and *Sorghum bicolour* (Pandey et al. 2005). Although there is a restriction on the movement of Cr from the roots to the aerial parts of the plant, the chemical form of Cr can still affect the movement of Cr from the roots to the aerial parts of the plant. In particular, the application of exogenous EDTA (ethylenediaminetetraacetic acid) to the plants increases the uptake of Chromium and its translocation from the roots of the plants to their upper parts (Pandey et al. 2005).

14.10 Research Regarding the Effects of Cr Stress on Plants Has Recently Made Significant Advances

Even though many studies have been conducted regarding the effects of chromium stress on plants in the past, the exact molecular mechanisms involved in the effects of chromium phytotoxicity, plant defence against chromium exposure, as well as the translocation and accumulation of chromium in plants, in general, remain poorly understood (Dubey 2010). Despite this, due to the progress that has been made in recent years in the field of omics, investigations of this nature can now be conducted with a much-increased degree of precision, and a wider range of variables associated with physiological responses to Cr stress can now be considered. A significant amount of potential exists in the "omics" fields when it comes to studying the underlying mechanisms responsible for the toxicological effects of chemical pollutants, as well as the identification of new biomarkers of effect that will be generated as a consequence of this potential (Dowling and Sheehan 2006).

14.11 The Molecular Mechanisms by Which Cr is Detoxified in Plants

There are two main defence mechanisms that plants have developed to protect themselves from the potentially harmful effects of Chromium. There are two types of avoidance: avoidance and tolerance. Tolerance is believed to be caused by genes and proteins that play a role in the uptake and translocation of Chromium, the chelation process, and the sequestration of Chromium in the vacuoles. A chemical compound called chromium is capable of causing the death of cells in the body. The study published by Liu (2008) indicates that a reduction in S levels activates the detoxification of Cr(VI) or tolerance in wild-type Scenedesmus acutus strains through a decrease in the amount of Cr(VI) taken up by the cells during the detoxification process. In the absence of sulphate, the activation of "high-affinity sulphate transporters" led to a greater uptake of sulphur than of chromium, which led to a lower rate of chromium uptake (VI) when there was no sulphate present. In addition, S-starvation activated the S-uptake/assimilation pathway, which led to the production of S-containing molecules (GSH, PCs, or MTs) as a result of the process of S-starvation. It is these molecules that are ultimately responsible for the cells' ability to tolerate Cr(VI) in the long run.

14.11.1 Avoidance

As the first step in protecting plants from the harmful effects of chromium, it is necessary to prevent the roots from being able to absorb more of the element from

the soil. Plant species that accumulate Cr, including aquatic plants and terrestrial plants, bind Cr ions to their cell walls, which are primarily composed of pectic sites, callose, and mucilage. In turn, this causes a reduction in the amount of Cr that is translocated into the cytosol in these plants (Vernay et al. 2007). Further, according to Ahmad et al. (2011), Cr ions are bound to the secondary cell wall by lignin, which also means that lignin plays a role in the binding of Cr ions to this cell wall. As demonstrated in a previous study (Samantaray 2002), the cell wall can act as a barrier to prevent Cr translocation through the cell, a function that is demonstrated by the accumulation of callose within the cell wall of Oryza *sativa* as well as the elevated expression of proteins related to the structure of the cell wall. The importance of the cell wall can be seen in both of these findings.

14.11.2 Antioxidant Response

As a result of Cr toxicity in plants, reactive oxygen species (ROS) are produced by the Fenton and Haber-Weiss reactions (Ganesh et al. 2008), which are then followed by the modulation of antioxidant enzyme activities. Plants are protected against reactive oxygen species (ROS) that are produced in response to calcium stress by the increased activity of antioxidant enzymes such as POD, catalase (CAT), APX, and SOD. Several antioxidant enzymes are involved in the interception of the chain reaction of free radicals, which either completely stops the oxidation process or significantly slows it down. Studies conducted on *Z. mays*, *Solanum lycopersicum*, and *B. oleracea* showed that Cr (VI) treatments increased glutathione (GSH) levels in both the roots and the leaves (Nath 2008). On the other hand, when *Jatropha curcas* was exposed to Cr, GSH activity was down (Joshi et al. 2003). A study conducted by Sharma et al. (1995a, b) found that in response to Cr stress, there is an increase in glutathione reductase activity (GR), one of the key enzymes in the Ascorbate-Glutathione pathway. Further to its role as a substrate for the biosynthesis of PCs, GR also serves as a metal chelator and a scavenger of oxygen radicals. This is in addition to its role as a substrate. As a result of a recent study on Miscanthus sinensis, it was found that upon exposure to 0.50 mM Cr, there was an overexpression of 36 proteins that are involved in oxidative stress, metabolism, molecular chaperone functions, among others (Subrahmanyam 2008).

14.11.3 Reduction of Cr(VI)–Cr(III)

Several chemical or enzymatic methods can be used to reduce Cr(VI)–Cr(III) so that there can be a reduction in the toxicity of Cr in plants. Plant cells can undergo this reduction chemically with the assistance of glutathione, cysteine, sulfite, and thiosulfate which are already present in the plant cell (Juarez 2008). It has been demonstrated that numerous bacteria associated with rhizospheric soils, such as

Bacillus species, Staphylococcus species, Ochrobacterium intermedium species, Pseudomonas species, Mesorhizobium species, and Cellulosimicrobium species, are capable of enzymatic reduction (Joshi 2003). In the electron transfer chain, these bacteria use chromate as the terminal electron acceptor of the electron transfer chain in the rhizosphere (Appenroth et al. 2001). These organisms possess both soluble and membrane-bound reductases.

14.11.4 An Approach to the Decontamination of Cr Using Phytoremediation

In the past few decades, scientists have studied tolerant and hyperaccumulator plants to learn more about how they work. In addition, they have also studied how they can be used as part of the phytoremediation process. As of now, nearly 500 plant species belonging to more than 45 plant families have been discovered. In the majority of the tolerant hyperaccumulator plants, the toxic metals were converted into forms that were less hazardous and could not be moved by the plant (Han et al. 2004). Most of the time, high-affinity ligands such as amino acids, peptides, and organic acids are what make the Cr hyper-accumulators work because they bind to receptors with high affinity. It is these ligands that chelate the metal ions and store them within the vacuoles of the cells. It is due to the increased mobilisation of metals from the rhizosphere by organic acids, their absorption by different families of transporters, and their movement into the shoot through xylem loading that Cr and other heavy metals accumulate too much in the plant. These factors are responsible for the excess accumulation of Cr and other heavy metals in the plant (Kleiman and Cogliatti 1997).

14.11.5 Phytoremediation by Hyperaccumulating Plants

To reduce the harmful effects of Cr exposure on the environment, phytoremediation could prove to be an approach that is both highly effective and relatively inexpensive. It uses plants to clean up contaminated soil and wastewater, which is both friendly to the environment and friendly to the environment as well. The results of numerous scientific studies have demonstrated that a variety of plant species can effectively remove Cr from polluted areas, which suggests that these plants could potentially be useful for the phytoremediation of polluted areas. As part of the phytoremediation process, there may be an opportunity to use a novel plant that has a long history of use in traditional Chinese medicine called Lonicera japonica Thunb, which has been used for centuries to accumulate Cr. According to Kim et al. (2006), one of the mechanisms explaining how these plants were able to tolerate Cr was their ability to produce anthocyanins, oxalic acid, and carotene in greater quantities. According to a study published in 2009 by Zhang et al., the macrophyte Callitriche cophocarpa can

be used as an efficient biosorbent for removing Chromium from concentrated solutions, which are typical of industrial effluents (Zhang et al. 2009). A study published by Shanker et al. (2005) demonstrated that Vigna unguiculata has a significantly higher capacity to remove Cr than Arachis hypogea, making these plants a more promising candidate for the phytoremediation of soils contaminated with chromium. As opposed to accumulating Cr in their aerial parts, V. unguiculata accumulated it in their roots from the surrounding soil, instead of accumulating it in their aerial parts. It was found by Levizou et al. (2018) that Origanum vulgare has an exceptional capacity to bioaccumulate chromium both in the aerial part and in the roots when grown in chromium-contaminated soil, as evidenced by the results of an experiment that was carried out on both an indoor and an outdoor scale in a pot. Following Afonso et al. (2019) research, species of Solanum viarum Dunal accumulate high levels of chloride in their biomass when left to grow. The high level of bioavailability of these plants, means that they can be used for phytoremediation and are likely to be effective at treating areas that are contaminated with heavy metals such as chromium. In an empirical study conducted by Marieschi et al. (2015), the Cassia tora plant was found to be a potential phytoremediator of Cr from contaminated sites because of its high bioaccumulation activity, high tolerance, and transportation index. As a result of this, the plant was able to apply the phytostabilization program, a program designed to lessen the toxicity of Cr on the mining sites that have been overburdened with chromite. *A crop called Arundo donax L. can handle moderate to high levels of heavy metals and can store a significant amount of Cr, which makes it a promising crop for energy production* (Mangabeira et al. 2011). It was found that the highest concentrations of Cr were found in the roots of Diectomis fastigiata (2371 mg/kg dry matter) and the shoots of Vernonia cinerea (5500 mg/kg dry matter). As a result of this, it can be seen that these plants are capable of removing Cr from the environment through phytoremediation. As an additional demonstration of its exceptional hyperaccumulation properties towards Cr, Callitriche cophocarpa Sendtn was planted in the heavily polluted watershed with sediments to demonstrate its exceptional hyperaccumulation properties towards heavy metal viz. chromium (Zeng et al. 2014). As part of a research project, it was discovered that the common water hyacinth, Eichhornia crassipes, has an effective capacity for removing chromium from water. The researchers used a small-scale hydroponic experiment with varying concentrations of metal for a period of one month. When compared to the accumulation in the shoot, the level of Cr found in the roots was significantly higher (Costa et al. 2010). The plant known as Cirsium vulgare is an effective accumulator of Cr and has the potential to be used effectively for the phytoremediation of soils that have been contaminated with Cr (Yadav et al. 2010). There is a possibility that the aquatic macrophyte Ipomoea aquatica can effectively remove Cr from water bodies in a relatively short amount of time, and that the species grows rapidly, so it may be an ideal candidate for phytoremediation of water bodies that are contaminated in elements (Sinha et al. 2018).

14.12 Detoxification of Cr Using Anti-Oxidant Machinery and Other Innovative Strategies

In terms of wastewater treatment, Ipomoea aquatica has the potential to be used in the treatment of wastewater that has high levels of Cr contamination (Sharmin et al. 2012). Moreover, Scoccianti et al. (2006) also cited that the fast-growing, tolerant, hyperaccumulating aquatic plants possessed a bio-accumulation and translocation factor equal to or greater than one, as well as demonstrating the ability to phytoremediation Chromium through bioaccumulation. It has been shown in earlier studies of this plant that it can be used in the treatment of effluents to remove Cr(VI), indicating that this plant has a high potential for use in the treatment of effluents as a source of the spontaneous removal of Cr(VI). Additionally, the researchers were able to demonstrate that when the anti-oxidant machinery was treated with Chromium, only minor alterations were observed, compared to the control group (Shanker et al. 2004). There has been a development of a method for removing chromium from the environment in an innovative manner. The method utilized by this study involves the use of an iron-biochar nano-complex for immobilizing the bioavailable mobile fraction, the use of the hyperaccumulator Leersia hexandra for uptake, and the utilization of a microbial consortium to facilitate the plant's growth. When this system was used, L. hexandra was able to accumulate Cr at a rate ranging from 147.5 to 785.0 mg/kg biomass of plant tissue when this system was applied (Shahid et al. 2017). Remarkably, the leaves of *Salvia moorcroftiana* that have been chemically modified can be utilized as biomass for the biosorption detoxification of aqueous solutions (Huang et al. 2018). This is accomplished by the removal of Cr(IV) ions through endothermic and non-spontaneous thermodynamic processes. This could be a better alternative because it is cheap and has a high biosorption capacity. Besides being able to remove Cr(IV) from water, it can also be used in the removal of heavy metals such as Pb(II) (lead) and Cd(II) (cadmium). As a result of a greenhouse experiment, it was found that two free-floating macrophytes, Eichhornia sp. and Pistia sp., had the capability of increasing anti-oxidant activity and building up in water bodies that were contaminated with Cr(VI), meaning that they could be used to clean them up. The Gomphrena celosoides can accumulate a significant amount of chromium because of their elevated levels of proline and antioxidant enzyme activity (Whitacre 2010). Because of the high level of proline in Gomphrena celosoides, as well as the antioxidant enzyme activity that they produce, this plant can store a significant amount of chromium (Whitacre 2010). It is known that Calotropis procera accumulates a high concentration of Chromium, as well as increases the activities of the enzymes SOD, CAT, and GR in the presence of Chromium (Cervantes et al. 2001). Because of these properties, it can be used for phytoremediation of polluted arid soils that are contaminated with Chromium. There is a high level of Chromium accumulation in Calotropis procera.

14.13 Conclusions

There has been an increase in the amount of pollution caused by chromium in the environment. In addition, there is a growing recognition that chromium is a serious health risk for the biota. There is a need for more research into how plants protect themselves from the toxic effects of this metal. It was in this chapter that we explored various negative effects that being exposed to Chromium can have on plants. This was from both the perspective of their morphology and their physiological reactions. In addition to the detrimental effects caused by Cr on plants, several toxic effects can be induced by Cr on plants, including altering germination and the growth process of roots, stems, and leaves. Additionally, Cr can adversely affect the morphological and physiological processes of plants, including photosynthesis, water relations, mineral nutrition, germination, and stem growth. It should be noted that Cr can also cause oxidative stress in plant cells by disrupting the balance of redox within the cells on a molecular level, in addition to causing oxidative stress in plant cells. As mentioned in the chapter, plants have a variety of ways of protecting themselves from external threats. While many of these defences are still not well understood, recent advances in molecular and cellular biology, such as genomics, proteomics, and the newly created field of metallomics, are shedding more light on the complex strategies plants use to protect themselves against such threats. Furthermore, there is a dearth of research in this area because these spheres of expertise have only relatively recently begun to be applied to environmental problems and have resulted in a lack of research in this area. In the future, certain constraints, such as the need for advanced mass spectrometry equipment and its hyphenations in the case of proteomics and metallomics, may continue to prevent development in the field; however, these constraints are becoming, increasingly, becoming cheaper and more readily available, and additional research in this field is just around the corner, which is why this area continues to grow (Table 14.1).

Table 14.1 Efficient chromium accumulator plants: habitat, culture conditions and removal mechanism

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
Brachiaria mutica (Paragrass)	Poaceae	Perennial grass	NR	Soil field study (mine wastewater)	Transportation index (TI): 6.16 Total accumulation rate (TAR):8.2 mg/kg/day	100 days	0.65 and 0.74 mg/L for Cr(VI)	Mohanty and Patra (2012)
Amaranthus viridis (Green amaranth)	Amaranthaceae	Perennial broadleaf herb	Increased activity of antioxidative enzymes	Hydroponic culture	Cr accumulation: Roots: 2624.39 mg/g Cr(VI) (dw) at 5.2 mg/L	20 days	0.052e5.2 mg/L Cr(VI)	Liu et al. (2008)
Dicoma niccolifera	Asteraceae	Terrestrial	NR		Cr accumulation: >1000 mg/kg Cr			Banach et al. (2012)
Helianthus annuus (Sunflower)	Asteraceae	Annual forb	NR	Cr contaminated soil	70% chromium removal Cr accumulation: Roots (2730 mg Cr/kg dry tissue)	90 days	10 mg/L Cr(VI)	Ranieri et al. (2013)
Azolla (Water fern)	Salviniaceae	Aquatic fern	NR	Hydroponic culture	Cr accumulation: 356 and 964 mg/kg dm Cr(VI) and Cr(III) at 1 mg/dm	12 days	1–20 mg/L Cr(VI)	Arora et al. (2006)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
Brassica juncea (Indian mustard)	Brassicaceae	Annual growing perennial herb	NR	Soil condition	Cr accumulation: 48 and 58 mg Cr per plant from Cr(III) and Cr(VI)-treated soils	69 days	Soil amended with 100 mg/ kg of Cr(III or VI)	Bluskov et al. (2005)
Leersia hexandra (Southern cutgrass)	Poaceae	Perennial herb (grow in swamps)	Facilitates microbial growth	CWs (Lab-scale)	99.7%	120 days	5 mg/L Cr(VI)	Liu et al. (2015)
			Cr(VI) reduction and sequestration	Hydroponic culture	Highest bioaccumulation coefficients for leaves: 486.8 for Cr(III) and 72.1 for Cr(VI)	45 days	10 mg/L Cr(VI) and 60 mg/L Cr(III)	Zhang et al. (2007)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
Eichhornia crassipes (Water hyacinth)	Pontederiaceae	Free-floating perennial aquatic plant	Increased activity of antioxidative enzyme Cr(VI) reduction	Hydroponic culture	Maximum Cr accumulation: 2.52 _ 103 mg/g of water hyacinth in 20 mg/L Cr removal efficiency: 91%	42 days	3, 5, 7, 10 and 20 Cr(VI) mg/L	Zewge et al. (2011)
			Plants exposed to 520 mg/L Cr(VI) for 4 days did not survive	Hydroponic culture under greenhouse conditions	Maximum Cr accumulation: 1258 mg/kg (dw) 520 mg/L Cr(III) for 2 days	2–4 days	52 and 520 mg/L Cr(III) and Cr(VI)	Mangabeira et al. (2004)
Prosopis laevigata (Smooth Mesquite)	Fabaceae	Flowering tree	NR	Tissue culture conditions	Cr accumulation: roots: 8090 mg/ kg Cr(VI) (dw)	50 days	0–176.8 mg/L Cr(VI)	Buendía-González et al. (2010)
Bacopa monnieri (Smooth water hyssop)	Plantaginaceae	Perennial, creeping herb	NR	Hydroponic conditions	319.5 mg/kg DW for Cr at 10 mg/ml	8 weeks	0.01, 0.1, 1.0, 2.5, 5.0, 10 mg/L Cr	Shukla et al. (2007)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
Phalaris arundinacea (Reed canarygrass)	Poaceae	Perennial grass	NR	Horizontal subsurface flow CW	Cr accumulation: 14.7 mg/kg dry mass Roots: 18.5 mg/ kg Cr	4 years	Municipal sewage with 0.5e4 mg/L Cr	Vymazal et al. (2007)
Hydroctyle umbellata (Marshpennywort)	Araliaceae	Anchored hydrophyte	NR	Hydroponic culture	Cr accumulation: 18,200 mg/kg	90 days	Semi-solid tannery (wet) sludge at 0, 20, 40, and 60% total Cr concentrations	Khilji (2008)
Convolvulus arvensis (Bindweed)	Convolvulaceae	Herbaceous perennial plant	NR	Tissue culture conditions	Cr accumulation: 3800 mg/kg Cr(VI) (dw)		20 mg/L Cr(VI)	Gardea-Torresdey et al. (2004)
Vetiveria zizanoides (Khas-khas)	Poaceae	Perennial grass	NR	Hydroponic culture CW	77–78% for Cr uptake ability	–	5–20 mg/L	Singh et al. (2015)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
					Max Cr accumulation: Stem (28.3 g/kg) 89.29% removal efficiency Cr accumulation: Roots 0.448 mg/kg (dw) Leaves 0.241 mg/kg (dw)	100 days	NR	Srisatit and Sengsai (2003)
Spirodela polyrrhiza (Giant duckweed)	Lemnaceae	Perennial aquatic plant	NR	Continuous flow pond system	Maximum Cr accumulation: 4.423 mg Cr/g was found in plants grown in the first chamber of pond operated at pH 4.0 at 5.0 mg Cr/L	21 days	0.25–5.0 mg/L Cr(VI)	Mishra and Tripathi (2008)
Genipa americana L (Genipap)	Rubiaceae	Wood plant	NR	Hydroponic conditions	–	5 months	0, 5, 10, 15, 20, 25 and 30 mg/L Cr(III)	Barbosa et al. (2007)
				Hydroponic conditions	Reduction of 79 and 90% for 15 and 30 mg/L of Cr(VI)	15 days	15 and 30 mg/L Cr(III) and Cr(VI)	Santana et al. (2012)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
Miscanthus sinensis (Chinese silver grass)	Poaceae	Herbaceous perennial plant	Altered vacuole sequestration, nitrogen metabolism and lipid peroxidation	Hydroponic culture	–	3 days	0, 2.6, 5.2, 10.4, 15.6, 26, 39 or 52 mg/L Cr(VI)	Sharmin et al. (2012)
Pteris vittata (Chinese brake)	Pteridaceae	Fern species	NR	Hydroponic system	Cr accumulation: Fronds 234 mg/kg (dw) Roots 12,630 mg/kg (dw) at 2.6 mg/L Cr(VI)	14 days	0, 2.6, 13 and 65 mg/L	de Oliveira et al. (2014)
Salvinia minima (Water spangles)	Salviniaceae	Aquatic macrophyte (Free floating fern)	Increased activity of antioxidative enzymes	Outdoor condition	Cr accumulation: Submerged leaves 3358 mg/g Cr(VI) (dw) Floating leaves 637 mg/g Cr(VI) (dw)	7 days	26–208 mg/L Cr(III) or Cr(VI)	Prado et al. (2012)
Leersia hexandra (Southern cutgrass)	Poaceae	Perennial herb (grow in swamps)	Facilitates microbial growth	CWs (Lab-scale)	99.7%	120 days	5 mg/L Cr(VI)	Liu et al. (2015)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
			Cr(VI) reduction and sequestration	Hydroponic culture	Highest bioaccumulation coefficients for leaves: 486.8 for Cr(III) and 72.1 for Cr(VI) Chromium accumulated in leaves was 4868 mg Cr (III)/g and 597 mg Cr (VI)/ g	45 days	10 mg/L Cr (VI) and 60 mg/L Cr (III)	Zhang et al. (2007)
Callitricha cophocarpa (Water-starwort)	Callitrichaceae	Aquatic macrophyte	Cr(VI) reduction	Hydroponic culture Wetland	Cr accumulation: 1000 mg/kg (dw)	3 weeks	2.6e36.4 mg/L Cr(VI)	Augustynowicz et al. (2020)
					Cr(VI) storage vascular bundles	7 days	5.2 mg/L Cr(III) and Cr(VI)	Augustynowicz et al. (2014)
					Cr accumulation: Cr(III) 28,385 mg/kg (dw)	5 days	26–208 mg/L Cr(III)	
Typha latifolia (Cattails) and *Phragmites australia* (Common reed)	Typhaceae Poaceae	Aquatic grass Perennial grass	NR	Horizontal subsurface flow CW	Maximum removal efficiency of 73%	17 months	Synthetic tannery waste water	Calheiros et al. (2007)

(continued)

Table 14.1 (continued)

Cr accumulator	Family	Habitat	Cr(VI) removal mechanism	Culture condition	Max % removal/ bioaccumulation capacity	Experimental period	Influent conc	References
Nymphaea spontanea (Water lilies)	Nymphaeaceae	Aquatic rhizomatous perennial herbs	NR	Hydroponic conditions	Cr accumulation: 2.119 mg/g from a 10 mg/L	9 weeks	1, 2.5, 5 and 10 mg/L Cr(VI)	Choo et al. (2006)
Spartina argentinensis (Cordgrass)	Poaceae	Perennial grass	NR	Glasshouse experiment	Cr accumulation: 15.1 mg/g Cr (VI) (dw) at 1040 mg/L	15 days	0–1040 mg/L Cr(VI)	Redondo-Gómez et al. (2011)
Gynura pseudochina (Purple passion)	Asteraceae	Herb	Cr (VI) reduction	Hydroponic culture	Cr accumulation: Tubers: 823.1 mg/kg Cr(VI) (dw) Shoots: 787.9 mg/kg Cr(VI) (dw)	2 weeks	100 mg/L Cr(VI)	Mongkhonsin et al. (2011)
Lemna sp. (Duckweed)	Araceae	Free-floating aquatic plants	NR	Hydroponic culture	4.423 mg Cr(VI)/g	7 days	5.0 mg/L Cr(VI) pH 4.0	Uysal (2013)
Salsola kali (Russian thistle)	Chenopodiaceae	Annual saltwart	NR	Agar based media	Maximum Cr accumulation at 20 mg/L Cr(VI): Roots: 2900 mg/kg Cr(VI) (dw) Stems: 790 mg/kg Cr(VI) (dw) Leaves:600 mg/kg Cr(VI) (dw)	15 days	0, 5, 10, and 20 mg/L Cr(VI)	Gardea-Torresdey et al. (2005)

Acknowledgements For their consistent support throughout the writing process, the authors would like to extend their sincere thanks to the Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India.

References

Afonso TF, Demarco CF, Pieniz S, Camargo FAO, Quadro MS, Andreazza R (2019) Potential of SolanumviarumDunal in use for phytoremediation of heavy metals to mining areas, Southern Brazil. Environ Sci Pollut Res 26:24132–24142

Ahmad M, Wahid A, Ahmad SS, Butt ZA, Tariq M (2011) Ecophysiological responses of rice (*Oryza sativa* L.) to hexavalent chromium. Pak J Bot 43:2853–2859

Ali NA, Ater M, Sunahara GL, Robidoux PY (2004) Phytotoxicity and bioacuumulation of copper and chromium using barley (*Hordeum vulgare* L.) in spiked artificial and natural forest soils. Ecotoxicol Environ Saf 57(3):363–374.

Ali S, Bai P, Zeng F, Cai S, Shamsi IH, Qiu B, Zhang G (2011) Theecotoxicological and interactive effects of chromium and aluminum on growth, oxidative damage and antioxidant enzymes on two barley genotypes differing in Al tolerance. Environ Exp Bot 70(2):185–191

Ali B, Huang CR, Qi ZY, Ali S, Daud MK, Geng XX, Zhou WJ (2013) 5- Amino levulinic acid ameliorates cadmium-induced morphological, biochemical, and ultra structural changes in seedlings of oil seedrape. Environ Sci Pollut Res 20(10):7256–7267

Ali S, Bharwana SA, Rizwan M, Farid M, Kanwal S, Ali Q, Khan MD (2015a) Fulvic acid mediates chromium (Cr) tolerance in wheat (Triticum aestivum L.) through lowering of Cr uptake and improved antioxidant defense system. Environ Sci Pollut Res 22(14):10601–10609

Ali S, Chaudhary A, Rizwan M, Anwar HT, Adrees M, Farid M, Anjum SA (2015b) Alleviation of chromium toxicity by glycine betaine is related to elevated antioxidant enzymes and suppressed chromium uptake and oxidative stress in wheat (Triticum aestivum L.). Environ Sci Pollut Res 22(14):10669–10678

Alloway B (2013) Introduction. Heavy metals in soils. B. J. Alloway. Springer Netherlands, vol 22, pp 3–9

Anderson AJ, Meyer DR, Mayer FK (1972) Heavy metal toxicities: levels of nickel, cobalt and chromium in the soil and plants associated with visual symptoms and variation in growth of an oat crop. Aust J Agric Res 24:557–571

Appenroth KJ, Stöckel J, Srivastava A, Strasser RJ (2001) Multiple effects of chromate on the photosynthetic apparatus of *Spirodela polyrhiza* as probed by OJIP chlorophyll a fluorescence measurements. Environ Pollut 115:49–64

Appenroth KJ, Keresztes A, Sárvári É, Jaglarz A, Fischer W (2003) Multiple effects of chromate on Spirodela polyrhiza: electron microscopy and biochemical investigations. Plant Biol 5:315–323

Augustynowicz J, Sitek E, Bryniarski T, Baran A, Ostachowicz B, Urbańska-Stopa M, Szklarczyk M (2020) The use of Callitrichecophocarpa Sendtn. for the reclamation of Cr-contaminated freshwater habitat: benefits and limitations. Environ Sci Pollut Res 27:25510–25522

Barcelo J, Poshenrieder CH (1997) Chromium in plants. In: Canali S, Tittarelli F, Sequi P (eds) Chromium environmental issues. Franco Angeli Publisher, Milano, pp 101–129

Barton LL, Johnson GV, O'Nan AG, Wagener BM (2000) Inhibition of ferric chelate reductase in alfalfa roots by cobalt, nickel, chromium, and copper. J Plant Nutr 23:1833–1845

Biacs PA, Daood HG, Kadar I (1995) Effect of Mo, Se, Zn, and Cr treatments on the yield, element concentration, and carotenoid content of carrot. J Agric Food Chem 43:589–591

Bishnoi NR, Chugh LK, Sawhney SK (1993a) Effect of chromium on photosynthesis, respiration and nitrogen fixation in pea (Pisum sativum L) seedlings. J Plant Physiol 142:25–30

Bishnoi NR, Dua A, Gupta VK, Sawhney SK (1993b) Effect of chromium on seed germination, seedling growth and yield of peas. Agric Ecosyst Environ 47:47–57

Cervantes C, Campos-García J, Devars S, Gutiérrez-Corona F, Loza- Tavera H, Torres-Guzmán JC, Moreno-Sánchez R (2001) Interactions of chromium with microorganisms and plants. FEMS Microbiol Rev 25:335–347

Chandra P, Sinha S, Rai UN (1997) Bioremediation of Cr from water and soil by vascular aquatic plants. In: Kruger EL, Anderson TA, Coats JR (eds) Phytoremediation of soil and water contaminants. ACS Symposium Series, vol 664. Washington, DC7 American Chemical Society, pp 274–82

Chatterjee J, Chatterjee C (2000) Phytotoxicity of cobalt, chromium and copper in cauliflower. Environ Pollut 109:69–74

Choudhury S, Panda SK (2005) Toxic effects, oxidative stress and ultrastuctural changes in moss Taxithelium nepalense (Schwaegr.) Broth under chromium and lead phytotoxicity. Water Air Soil Pollut 167:73–90

Costa RC, Moura FC, Oliveira PE, Magalhães F, Ardisson JD, Lago RM (2010) Controlled reduction of red mud waste to produce active systems for environmental applications: heterogeneous Fenton reaction and reduction of Cr(VI). Chemosphere 78:1116–1120

Davies FT, Puryear JD, Newton RJ, Egilla JN, Grossi JAS (2002) Mycorrhizal fungi increase chromium uptake by sunflower plants: influence on tissue mineral concentration, growth and gas exchange. J Plant Nutr 25:2389–2407

Dhir B, Sharmila P, Saradhi PP, Nasim SA (2009) Physiological and antioxidant responses of Salvinia natans exposed to chromium rich wastewater. Ecotoxicol Environ Saf 72:1790–1797

Dixit V, Pandey V, Shyam R (2002) Chromium ions inactivate electron transport and enhance superoxide generation in vivo in pea (Pisum sativum L.cv. Azad) root mitochondria. Plant Cell Environ 25:687–690

Dowling VA, Sheehan D (2006) Proteomics as a route to identification of toxicity targets in ecotoxicology. Proteomics 6:5597–5604

Dube BK, Tewari K, Chatterjee J, Chatterjee C (2003) Excess chromium alters uptake and translocation of certain nutrients in Citrullus. Chemosphere 53:1147–1153

Dubey S (2010) Transcriptomic and metabolomic shifts in rice roots in response to Cr(VI) stress. BMC Genom 11:648–667

Förstner U, Wittmann GT (2012) Metal pollution in the aquatic environment. Springer, Berlin, Heidelberg, New York

Ganesh KS, Baskaran L, Rajasekaran S, Sumathi K, Chidambaram ALA, Sundaramoorthy P (2008) Chromium stress induced alterations in biochemical and enzyme metabolism in aquatic and terrestrial plants. Colloids Surf B Biointerfaces 63:159–163

Golovatyj SE, Bogatyreva EN, Golovatyi SE (1999) Effect of levels of chromium content in a soil on its distribution in organs of corn plants. Soil Res Fert 197–204

Gopal R, Rizvi AH, Nautiyal N (2009) Chromium alters iron nutrition and water relations of spinach. J Plant Nutr 32:1551–1559

Han FX, Sridhar BBM, Monts DL, Su Y (2004) Phyto-availability and toxicity of trivalent and hexavalent chromium to Brassica juncea. New Phytol 162:489–499

Hanus J, Tomas J (1993) An investigation of chromium content and its uptake from soil in white mustard. Acta Fytotech 48:39–47

Huang W, Jiao J, Ru M, Bai Z, Yuan H, Bao Z, Liang Z (2018) Localization and Speciation of Chromium in *Coptis chinensis* Franch. using synchrotron radiation X-ray technology and laser ablation ICP-MS. Sci Rep 8:8603

Huffman EWD, Allaway HW (1973a) Chromium in plants: distribution in tissues, organelles, and extracts and availability of bean leaf Cr to animals. J Agric Food Chem 21:982–986

Huffman EWD, Allaway WH (1973b) Growth of plants in solution culture containing low levels of chromium. Plant Physiol 52:72–75

Iqbal MZ, Saeeda S, Shafiq M (2001) Effects of chromium on an important arid tree (Caesalpinia pulcherrima) of Karachi city, Pakistan. Ekol Bratislava 20:414–422

Ishikawa S, Ae N, Murakami M, Wagatsuma T (2006) Is Brassica juncea a suitable plant for phytoremediation of cadmium in soils with moderately low cadmium contamination?—Possibility of using other plant species for Cd phytoextraction. Soil Sci Plant Nutr 52:32–42

Jain R, Srivastava S, Madan VK, Jain R (2000) Influence of chromium on growth and cell division of sugarcane. Indian J Plant Physiol 5:228–231

Joshi UN, Rathore SS, Arora SK (2003) Chromium induced changes in carbon and nitrogen metabolism in guar. In: Henry A, Kumar D, Singh NB (eds) Advances in arid legumes research, pp 355–360

Juarez AB, Barsanti L, Passarelli V, Evangelista V, Vesentini N, Conforti V, Gualtieri P (2008) In vivo microspectroscopy monitoring of chromium effects on the photosynthetic and photoreceptive apparatus of Eudorina unicocca and Chlorella kessleri. J Environ Monit 10:1313–1318

Kar D, Sur P, Mandal SK, Saha T, Kole RK (2008) Assessment of heavy metal pollution in surface water. J Environ Agric Food Chem 9:444–457

Karunyal S, Renuga G, Paliwal K (1994) Effects of tannery effluent on seed germination, leaf area, biomass and mineral content of some plants. Bioresour Technol 47:215–218

Kim YJ, Kim JH, Lee CE, Mok YG, Choi JS, Shin HS, Hwanga S (2006) Expression of yeast transcriptional activator MSN1 promotes accumulation of chromium and sulfur by enhancing sulfate transporter level in plants. FEBS Lett 580:206–210

Kleiman ID, Cogliatti DH (1997) Uptake of chromate in sulfate-deprived wheat plants. Environ Pollut 1–2:131–135; Environ Chem Lett 11:229–254 249

Kocik K, Ilavsky J. Effect of Sr and Cr on the quantity and quality of the biomass of field crops. In: Production and utilization of agricultural and forest biomass for energy: proceedings of a seminar held at Zvolen, Slovakia, pp 168–178

Kumar M, Puri A (2012) A review of permissible limits of drinking water. Indian J Occup Environ Med 16(1):40

Levizou E, Zanni AA, Antoniadis V (2018) Varying concentrations of soil chromium (VI) for the exploration of tolerance thresholds and phytoremediation potential of the oregano (Origanum vulgare). Environ Sci Pollut Res 26:14–23

Liu DH, Jaing WS, Li MX (1993) Effect of chromium on root growth and cell division of Allium cepa. Isr J Plant Sci 42:235–243

Liu D, Zou J, Wang M, Jiang W (2008) Hexavalent chromium uptake and its effects on mineral uptake, antioxidant defence system and photosynthesis in Amaranthus viridis L. Biores Technol 99:2628–2636

Mandich NV (1997) Chemistry & theory of chromium deposition: Part 1–Chemistry. Plat Surf Finish 84(5):108–115

Mangabeira PA, Ferreira AS, de Almeida AAF, Fernandes VF, Lucena E, Souza VL, dos Santos-Júnior AJ, Oliveira AH, Grenier-Loustalot MF, Barbier F (2011) Compartmentalization and ultrastructural alterations induced by chromium in aquatic macrophytes. Biometals 24:1017–1026

Marieschi M, Gorbi G, Zanni C, Sardella A, Torelli A (2015) Increase of chromium tolerance in Scenedesmusacutus after sulfur starvation: chromium uptake and compartmentalization in two strains with different sensitivities to Cr(VI). Aquat Toxicol 167:124–133

McGrath SP (1995) Chromium and nickel. In: Alloway BJ (ed) Heavy metals in soils. Blackie Academic and Professional, London, pp 152–217

Mushtaq Z, Asghar HN, Zahir ZA (2021) Comparative growth analysis of okra (Abelmoschus esculentus) in the presence of PGPR and press mud in chromium contaminated soil. Chemosphere 262:127865

Nagajyoti PC, Lee KD, Sreekanth TVM (2010) Heavy metals, occurrence and toxicity for plants: a review. Environ Chem Lett 8(3):199–216

Nath K, Singh DH, Shyam S, Sharma YK (2008) Effect of chromium and tannery effluent toxicity on metabolism and growth in cowpea (Vigna sinensis L. SaviexHassk) seedling. Res Environ Life Sci 1(3):91–94

Nichols PB, Couch JD, Al-Hamdani SH (2000) Selected physiological responses of Salvinia minima to different chromium concentrations. Aquat Bot 68:313–319
Ogundiran O, Afolabi TA (2008) Assessment of the physicochemical parameters and heavy metal toxicity of leachates from municipal solid waste open dumpsite. Int J Environ Sci Technol 5:243–250
Paiva LB, de Oliveira JG, Azevedo RA, Ribeiro DR, da Silva MG, Vitória AP (2009) Ecophysiological responses of water hyacinth exposed to Cr3+ and Cr6+. Environ Exp Bot 65:403–409
Panda SK, Patra HK (2000) Nitrate and ammonium ions effect on the chromium toxicity in developing wheat seedlings. P Natl Acad Sci India B 70:75–80
Panda SK, Mahapatra S, Patra HK (2002) Chromium toxicity and water stress simulation effects in intact senescing leaves of green gram (Vigna radiata L. var Wilckzeck K851). In: Panda SK (ed) Advances in stress physiology of plants. Scientific Publishers, Jodhpur, India, pp 129–136
Pandey V, Dixit V, Shyam R (2005) Antioxidative responses in relation to growth of mustard (Brassica juncea cv. Pusa Jaikisan) plants exposed to hexavalent chromium. Chemosphere 61:40–47
Pandey V, Dixit V, Shyam R (2009) Chromium effect on ROS generation and detoxification in pea (Pisum sativum) leaf chloroplasts. Protoplasma 236(1–4):85–95
Papp JF, Lipin BR, Kirk-Othmer O (2010) Encyclopedia of chemical technology. Wiley. http://onlinelibrary.wiley.com
Pedreno NJI, Gomez R, Moral G, Palacios J, Mataix J (1997) Heavy metals and plant nutrition and development. Recent Res Dev Phytochem 1:173–179
Peralta JR, Gardea Torresdey JL, Tiemann KJ, Gomez E, Arteaga S, Rascon E (2001) Uptake and effects of five heavy metals on seed germination and plant growth in alfalfa (Medicago sativa) L. B Environ Contam Toxicol 66(6):727–734
Polti MA, Atjián MC, Amoroso MJ, Abate CM (2011) Soil chromium bioremediation: synergic activity of actinobacteria and plants. Int Biodeterior Biodegrad 65(8):1175–1181
Poschenrieder C, Gunse B, Barcelo J (1993) Chromium-induced inhibition of ethylene evolution in bean (Phaseolus vulgaris) leaves. Physiol Plant 89:404–408
Prasad MNV, Greger M, Landberg T (2001) Acacia nilotica L bark removes toxic elements from solution: corroboration from toxicity bioassay using Salix viminalis L in hydroponic system. Int J Phytoremed 3:289–300
Prasad S, Yadav KK, Kumar S, Gupta N, Cabral-Pinto MM, Rezania S, Radwan N, Alam J (2021) Chromium contamination and effect on environmental health and its remediation: a sustainable approaches. J Environ Manag 285:112174
Pulford ID, Watson C, McGregor SD (2001) Uptake of chromium by trees: prospects for phytoremediation. Environ Geochem Health 23:307–311
Rai UN, Tripathi RD, Kumar N (1992) Bioaccumulation of chromium and toxicity on growth, photosynthetic pigments, photosynthesis, in vivo nitrate reductase activity and protein content in chlorococcalear green alga, Glaucocystis nostochinearum ltzigsohn
Rai V, Vajpayee P, Singh SN, Mehrotra S (2004) Effect of chromium accumulation on photosynthetic pigments, oxidative stress defense system, nitrate reduction, proline level and eugenol content of Ocimum tenuiflorum L. Plant Sci 167:1159–1169
Rai V, Mehrotra S (2008) Chromium-induced changes in ultramorphology and secondary metabolites of Phyllanthus amarus Schum & Thonn—An hepatoprotective plant. Environ Monit Assess 147:307–315
Redondo-Gómez S, Mateos-Naranjo E, Vecino-Bueno I, Feldman SR (2011) Accumulation and tolerance characteristics of chromium in a cordgrass Cr-hyperaccumulator, Spartina argentinensis. J Hazard Mater 185:862–869
Rout GR, Samantaray S, Das P (1997) Differential chromium tolerance among eight mungbean cultivars grown in nutrient culture. J Plant Nutr 20:473–483
Samantaray S, Rout GR, Das P (1999) Studies on differential tolerance of mungbean cultivars to metalliferous minewastes. Agribiol Res 52:193–201

Samantaray S (2002) Biochemical responses of Cr-tolerant and Cr-sensitive mung bean cultivars grown on varying levels of chromium. Chemosphere 47:1065–1072
Scoccianti V, Crinelli R, Tirillini B, Mancinelli V, Speranza A (2006) Uptakeand toxicity of Cr(III) in celery seedlings. Chemosphere 64(10):1695–1703
Shahid M, Shamshad S, Rafiq M, Khalid S, Bibi I, Niazi NK, Dumat C, Rashid MI (2017) Chromium speciation, bioavailability, uptake, toxicity and detoxification in soil-plant system: a review. Chemosphere 178:513–533
Shanker AK, Djanaguiraman M, Sudhagar R, Chandrashekar CN, Pathmanabhan G (2004) Differential antioxidative response of ascorbate glutathione pathway enzymes and metabolites to chromium speciation stress in green gram (Vigna radiata (L) R Wilczek, cv CO4) roots. Plant Sci 166:1035–1043
Shanker AK, Cervantes C, Loza-Tavera H, Avudainayagam S (2005) Chromium toxicity in plants—A review. Environ Int 31:739–753
Sharma DC, Mehrotra SC (1993) Chromium toxicity effects on wheat (Triticum aestivum L cv HD 2204). Indian J Environ Health 35:330–332
Sharma DC, Pant RC (1994) Chromium uptake: its effects on certain plant nutrients in maize (Zea mays L. cv. Ganga 5). J Environ Sci Health 29:941–948
Sharma DC, Chatterjee C, Sharma CP (1995a) Chromium accumulation and its effects on wheat (Triticum aestivum L. cv. HD 2204) metabolism. Plant Sci 111:145–151
Sharma DC, Chatterjee C, Sharma CP (1995b) Chromium accumulation by barley seedlings (Hordeum vulgare L,). J Exp Bot 1995:25241–25251
Sharmin SA, Alam I, Kim KH, Kim YG, Kim PJ, Bahk JD, Lee BH (2012) Chromium-induced physiological and proteomic alterations in roots of Miscanthus sinensis. Plant Sci 187:113–126
Singh AK (2001) Effect of trivalent and hexavalent chromium on spinach (Spinacea oleracea L). Environ Ecol 19:807–810
Sinha V, Pakshirajan K, Chaturvedi R (2018) Chromium tolerance, bioaccumulation and localization in plants: an over-view. J Environ Manag 206:715–730
Smith WA, Apel WA, Petersen JN, Peyton BM (2002) Effects of carbon and energy source on bacterial chromate reduction. Bioremed J 6:205–215
Srivastava S, Nigam R, Prakash S, Srivastava MM (1999a) Mobilization of trivalent chromium in presence of organic acids: a hydroponic study of wheat plant (Triticum vulgare). Bull Environ Contam Toxicol 63:524–530
Srivastava S, Prakash S, Srivastava MM (1999b) Chromium mobilization and plant availability—The impact of organic complexing ligands. Plant Soil 212:203–208
Subrahmanyam D (2008) Effects of chromium toxicity on leaf photosynthetic characteristics and oxidative changes in wheat (Triticum aestivum L.). Photosynthetica 46:339–345
Sundaramoorthy P, Chidambaram A, Ganesh KS, Unnikannan P, Baskaran L (2010) Chromium stress in paddy: (i) nutrient status of paddy under chromium stress; (ii) phytoremediation of chromium by aquatic and terrestrial weeds. CR Biol 333:597–607
Suseela MR, Sinha S, Singh S, Saxena R (2002) Accumulation of chromium and scanning electron microscopic studies in *Scirpus lacustris* l treated with metal and tannery effluent. Bull Environ Contam Toxicol 68:540–548
Tang SR, Wilke BM, Brooks RR, Tang SR (2001) Heavy-metal uptake by metaltolerant Elsholtzia haichowensis and Commelina communis from China. Commun Soil Sci Plant Anal 32(5–6):895–905
Tiwari KK, Dwivedi S, Singh NK, Rai UN, Tripathi RD (2009) Chromium(VI) induced phytotoxicity and oxidative stress in pea (Pisum sativum L.): biochemical changes and translocation of essential nutrients. J Environ Biol 30:389–394
Tripathi AK, Tripathi S, Tripathi S (1999) Changes in some physiological and biochemical characters in Albizia lebbek as bio-indicators of heavy metal toxicity. J Environ Biol 20:93–98
Turner MA, Rust RH (1971) Effects of chromium on growth and mineral nutrition of soybeans. Soil Sci Soc Am Proc 35:755–758

Vajpayee P, Sharma SC, Tripathi RD, Rai UN, Yunus M (1999) Bioaccumulation of chromium and toxicity to photosynthetic pigments, nitrate reductase activity and protein content of Nelumbo nucifera Gaertn. Chemosphere 39:2159–2169

Vajpayee P, Tripathi RD, Rai UN, Ali MB, Singh SN (2000) Chromium (VI) accumulation reduces chlorophyll biosynthesis, nitrate reductase activity and protein content in Nymphaea alba L. Chemosphere 41:1075–1082

Vajpayee P, Rai UN, Ali MB, Tripathi RD, Yadav V, Sinha S, Singh SN (2001) Chromium induce physiologic changes in Vallisneria spiralis L. and its role in phytoremediation of tannery effluent. Bull Environ Contam Toxicol 67:246–256

Vernay P, Gauthier-Moussard C, Hitmi A (2007) Interaction of bioaccumulation of heavy metal chromium with water relation, mineral nutrition and photosynthesis in developed leaves of Lolium perenne L. Chemosphere 68:1563–1575

Whitacre DM (2010) In: Metzler JB (ed) Reviews of environmental contamination and toxicology, vol 202. Springer, New York, USA

Yadav SK, Dhote M, Kumar P, Sharma J, Chakrabarti T, Juwarkar AA (2010) Differential antioxidative enzyme responses of Jatrophacurcas L. to chromium stress. J Hazard Mater 180:609–615

Yoon J, Cao X, Zhou Q, Ma LQ (2006) Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. Sci Total Environ 368:456–464

Zayed AM, Terry N (2003) Chromium in the environment: factors affecting biological remediation. Plant Soil 249:139–156

Zeid IM (2001) Responses of Phaseolus vulgaris to chromium and cobalt treatments. Biol Plant 44:111–115

Zeng F, Wu X, Qiu B, Wu F, Jiang L, Zhang G (2014) Physiological and proteomic alterations in rice (Oryza sativa L.) seedlings under hexavalent chromium stress. Planta 240:291–308

Zhang D, Jiang L, Shao Y, Chai B, Li C (2009) Variations in germination and endogenous hormone contents of wheat cultivars under Cr stress. Chin J Appl Environ Biol 15:602–605

Zhitkovich A, Song Y, Quievryn G, Voitkun V (2001) Non-oxidative mechanisms are responsible for the induction of mutagenesis by reduction of Cr(VI) with cysteine: role of ternary DNA adducts in Cr(III)-dependent mutagenesis. Biochemistry 40(2):549–560

ZivKovic J, Razic S, Arsenijevic J, Maksimovic Z (2012) Heavy metal contents Zn Veronica species and soil from mountainous areas in Serbia. J Serb Chem Soc 77(7):959–970

Zurayk R, Sukkariyah B, Baalbaki R (2001) Common hydrophytes as bioindicators of nickel, chromium and cadmium pollution. Water Air Soil Pollut 127:373–388