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REVIEW

# Cadmium Toxicity in Plants: Recent Progress on Morpho-physiological Effects and Remediation Strategies

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## Abstract

Cadmium (Cd) is one of the non-essential, highly toxic environmental pollutants worldwide causing serious environmental and agricultural problems. Elevated Cd doses are carcinogenic to humans. It is ranked seventh in the list of top 20 toxic metals and classified as a group 1 carcinogen. The median range of Cd dietary intake (66.5–116 μg Cd $kg^{-1}$ body weight per month) is much higher than maximum limit (25 μg Cd $kg^{-1}$ body weight per month) reported by FAO/WHO. Toxicity of Cd causes a range of damages to plants from germination to yield; however, the extent of damage is concentration and time-dependent. Reduction in seed germination and plant growth is primarily due to Cd interference with enzymatic and photosynthetic activities and membrane damage. Cadmium exposure at higher rates disturbs the nutritional and water relations of plants and causes oxidative damage. Moreover, Cd-induced structural changes in the photosynthetic apparatus disturb the yield of plants. In this review, adverse effects of Cd on seed germination, stand establishment, plant growth, uptake and assimilation of nutrients, enzymatic activities, ultra-structural and oxidative damages, changes in antioxidant defense system and stress proteins, carbon metabolism, and yield formation are reported. Moreover, Cd dynamics in soil rhizosphere and factors affecting Cd dynamics in soil have also been discussed. Furthermore, remediation strategies (physical, chemical, biological, and amendments) to decontaminate Cd-polluted soils have also been described in this review. Through phytoremediation, Cd can be extracted and stabilized in the soil while through microbes Cd can be sequestrated into their bodies. Increased Cd uptake in hyperaccumulator plants to remediate and convert the toxic form of Cd into nontoxic forms. While in chemical remediation, Cd can be washed out, immobilized and stabilized in the soil through chemical amendments. Bioremediation of polluted sites is considered effective and reliable due to its eco-friendly features. Moreover, Cd uptake and toxicity in rice can be decreased by proper application of essential nutrients such as nitrogen, zinc, iron, and selenium in Cd contaminated soils. The organic amendments may help through an increase in soil pH, adsorption in its functional groups, the formation of complexations, and the conversion of exchangeable to residual forms. Adoption of some agricultural practices are also found to be effective in reducing the Cd uptake and accumulation in plants and harvesting quality food from Cd contaminated soils.

**Keywords** Cadmium toxicity · Inorganic amendments · Physiological responses · Oxidative damage · Phytoremediation

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## 1 Introduction

In the present era, environmental contamination is one of the significant constraints of modern human society (Ali and Khan 2017; Afzal et al. 2019). Among environmental contaminants, heavy metals (HMs) are the most toxic due to their persistent and bioaccumulative nature; thus, creating a deleterious risk to biological substances (Ali et al. 2019). Globally, the rate of HM mobilization and transport in the ecological system has been extraordinarily expanded since the 1940s due to rapid growth rate of industrialization (Anyanwu et al. 2018). Although, these metals naturally exist in the soil in a very minute concentration through characteristic lithogenic as well as pedogenic means (Wuana and Okieimen, 2011). However, various anthropogenic practices including mining, improper industrial as well as urban waste disposal, combustion of non-renewable energy sources, metallurgical industries, chemical fertilizers, and improper handling of industrial effluents are fundamental contributors to aggregate these metals in soil (Tchounwou et al. 2012; Yuan et al. 2019).

Regarding their biological role, HMs have been categorized primarily as essential as well as non-essential (Ali et al. 2019). Essential HMs like zinc (Zn), manganese (Mn), iron (Fe), and nickel (Ni) are inevitably vital for the growth and biological functioning of living forms in a quite low concentration (Andresen et al. 2018). While non-essential HMs including lead (Pb), cadmium (Cd), and silver (Ag) have no or very little biological activity and their exposure above permissible limit poses a hazard to biological systems by interfering with their physiological and metabolic processes, contaminating food chain, causing ecological imbalances and resulting in lethal health issues due to their toxic nature (Zulfiqar et al. 2019; Haider et al. 2021). Cadmium is a highly noxious HM that is deleterious for biological systems through its uptake and accumulation in phototrophs and consequent trophic transportation (Hussain et al. 2021a, b). According to ATSDR (2012), Cd has been classified as a 7th element amongst the top 20 most dangerous substances due to its extraordinary potential health effects. Cadmium is released into the environment via both natural and anthropogenic systems. Among natural systems, volcanic emissions, forest fires, weathering of Cd-containing rocks, and wastewater are the principal means of mobilizing it from the lithosphere (Choppala et al. 2014; Zhao et al. 2015). However, Cd is rare HM in the lithosphere which is ranked as 65th most abundant element with 0.1–0.2 ppm concentration (Emsley 2011). Therefore, anthropogenic activities such as application of phosphate-based fertilizers (Roberts 2014), manufacturing of Ni–Cd batteries, Zn mining, agricultural practices such as wastewater irrigation, electroplating, application of urban compost as well as metal-based pesticides, and industrial emission as a byproduct (Zhao et al. 2015; Zhou et al. 2017; Manzoor et al. 2019) are mainly responsible for Cd aggregation in soil. Additionally, atmospheric deposition is the key source of soil Cd accumulation with 2500–15,000 tonnes per annum (UNEP 2010; Shahid et al. 2013a; Cai et al. 2019). Between 2001 and 2019, global production of recoverable Cd increased from 19,300 to 25,400 thousand metric tons (USGS 2020; Fig. 1).

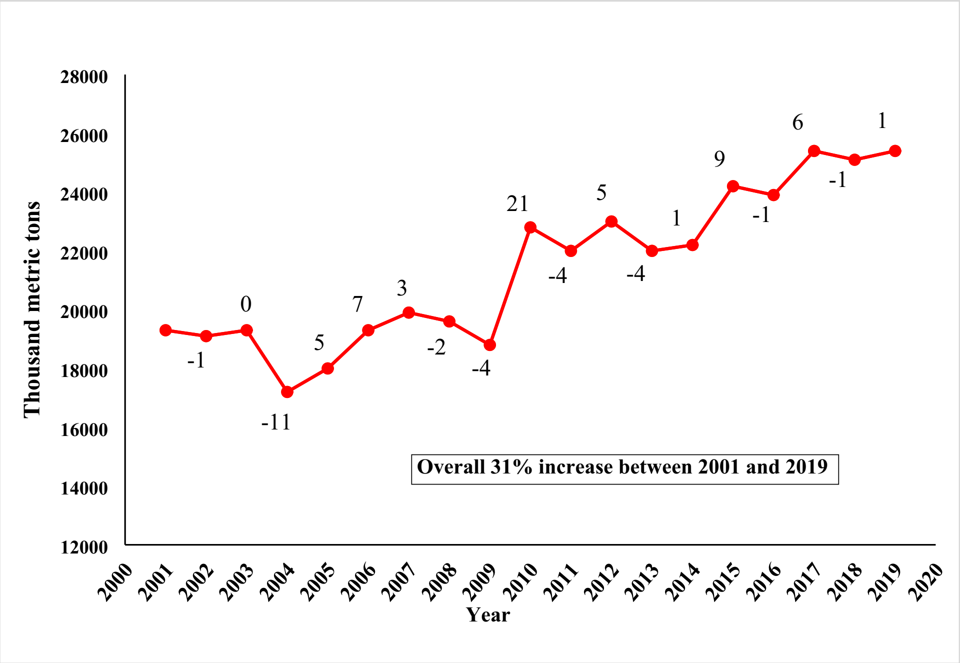

**Fig. 1** Annual world mine production of Cd in thousand metric tons (source, USGS 2020). The plus and minus values/labels in the graph line indicate the % increase and decrease of Cd production

Cadmium is a toxic heavy metal that has a little biological role in living bodies (Shahid et al. 2016). It has been demonstrated to be naturally used as a catalytic metal in the cadmium-carbonic anhydrase (CDCA1), a CA isolated from the marine diatom *Thalassiosira weissflogii* (Alterio et al. 2015). However, due to its great mobility in soil–plant framework (Gill et al. 2012), Cd is easily taken up by plants and transmitted to humans and animals along the food chain (Paunov et al. 2018); hence, its exposure in excessive concentration is a serious concern for them. In human beings, the maximum acceptable dietary Cd concentration is 60–70 µg per day (Chunhabundit 2016). Beyond this level, it is reported to associate with breathing and bone disorders, diabetes, hypertension (Ueno et al. 2010; Fatima et al. 2019) and elicits extreme damage to organs such as lungs, kidneys, and liver, causing the danger of emerging malignancy (Shahid et al. 2014a; Baldantoni et al. 2016). Moreover, it is highly detrimental for soil microbial community activities and structure (Khan et al. 2009a, b; Yu et al. 2021) and is also reported to impair plant physiological capacities, leading towards abridged growth and yield (Jibril et al. 2017). Therefore, to limit the risk of Cd-induced phytotoxicity, high Cd concentrations in foodstuff, and the subsequent impact on animals and human beings, it is suggested that agricultural lands with more than 1 ppm Cd may not be used for crop production and decontaminating measures should be adopted for soils having 5–20 ppm Cd concentration (Louwagie et al. 2009).

The fundamental ideas of Cd dynamics, its uptake, noxiousness, and detoxifying mechanisms in the soil–plant framework have been thoroughly scrutinized in studies conducted before 2000 and their findings have been summed up in numerous review articles and books. Moreover, during the recent decade, quite a few articles have further been documented, reflecting the biochemical mechanisms under Cd stress. The current review sums up the most recent data regarding the toxic effects of Cd on key metabolic functions of plants leading to growth and yield impairment. The dynamics of Cd in the rhizosphere, factors affecting its bioavailability along with important remediation approaches and agricultural practices are also highlighted to reclaim the Cd contaminated soils to harvest better crop yields of good quality.

## 2 Impact of Cadmium Toxicity on Plant Growth and Yield Formation

Beyond permissible limits, i.e., 8 ppm for agricultural soils as well as 3–30 ppm for plants ((Ismael et al. 2019), Cd is reported to elicit adverse effects on plant growth owing to its non-metabolic nature and extensive biological half-life (Shanmugaraj et al. 2019). Its excessive accumulation in plants reflects several phytotoxic features including abridged germination index, water and oxidative stress, impairment in nutrient uptake and metabolism, hampered enzymatic activities, genotoxicity, and impeded carbon metabolism; hence, leading towards a substantial decline in crop yield (Fig. 2; Shahid et al. 2013b, 2014b; Abedi and Mojiri 2020). Effects of Cd contamination on various aspects of phytotoxicity are highlighted in the accompanying sub-sections.

### 2.1 Germination, Stand Establishment, and Plant Growth

Cadmium causes obnoxious effects on germination index, seedling vigor index, and earlier plant growth (He et al. 2014). Reduced seed germination is attributed to the Cd-induced inhibition of seed imbibition (Bautista et al. 2013; Huybrechts et al. 2019) which is essential for hydration of enzymes involved in important metabolic activities, resulting in biochemical as well as physiological alterations (Zayneb et al. 2015). Moreover, high Cd concentration in germination medium appears to inhibit hydrolysis of reserved sugars as well as their translocation from endosperm to growing embryonic axis due to its contrary effects on hydrolyzing enzymes such as acid phosphatases (ACPs) and α-amylases, hence leading to starvation of germinating embryo (Kuriakose and Prasad 2008). Besides, Cd-induced retardation of seedling growth has also been reported due to inhibited storage protein catabolism owing to its interactions with proteolytic enzymes (Gianazza et al. 2007), changes in protein pattern (Ahsan et al. 2007a, b) and reduction in root respiration leading to augmented nitrite production (Gouia et al. 2003) and impaired cellular activities (Seneviratne et al. 2017). Several studies reported that Cd stress leads to inhibition of food storage mobilization, decrease in radical formation. Disruption in cellular osmoregulation and the degradation of proteolytic activities, ultimately inhibition of seed germination and seedlings development (Baszynski 2014; Seneviratne et al. 2017; Fig. 3). A series of recent studies has well documented the harmful effect of Cd on germination as well as seedling vigor index in a variety of crops including rice (*Oryza Sativa* L.) (Cd 100 µM) (He et al. 2014), wheat (*Triticum aestivum* L.) (Cd 20 mg $L^{-1}$) (Ahmad et al. 2013), maize (*Zea mays* L.) (Cd 100 mg $L^{-1}$) (Chen et al. 2021), sunflower (*Helianthus annuus* L.) (Cd 50 mg $kg^{-1}$) (Jadia and Fulekar 2008, mustard (*Brassica juncea* L.) (Cd 100 mg $kg^{-1}$) (Irfan et al. 2014), pea (*Pisum sativum*) (Cd 5 mM) (Smiri 2011), chickpea (*Cicer arietinum L.*) (Cd 23 mg $kg^{-1}$) (Wani et al. 2007a), mung bean (*Vigna radiate* L.) (Cd 23 mg $kg^{-1}$) (Wani et al. 2007b), and rapeseed (*Brassica napus* L.) (Cd 10 mg $kg^{-1}$) (Ehsan et al. 2014a).

In addition to germination and seedling growth, Cd contamination also causes plant growth deformities due to

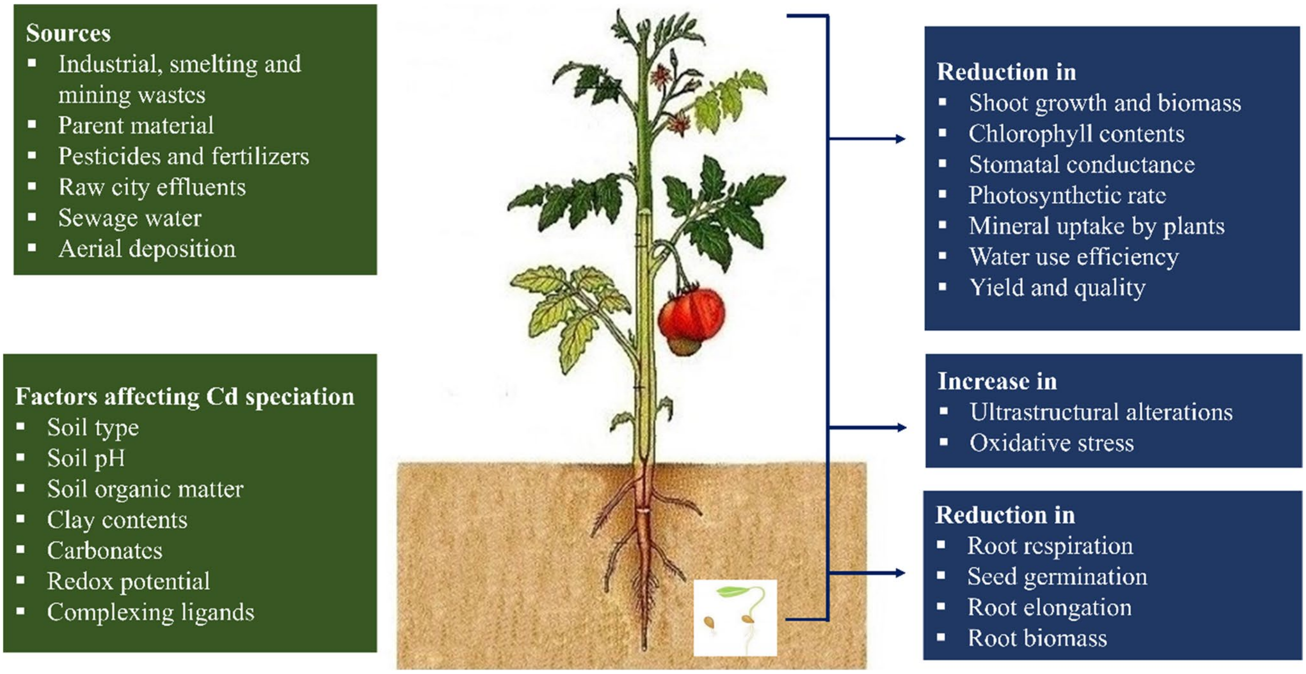

**Fig. 2** Possible sources of cadmium in soil, factors affecting cadmium speciation in soil, and its toxic impacts of cadmium in plant (Data taken from Khan et al. 2017; Rizwan et al. 2018; Yuan et al. 2019; El-Rasafi et al. 2020)

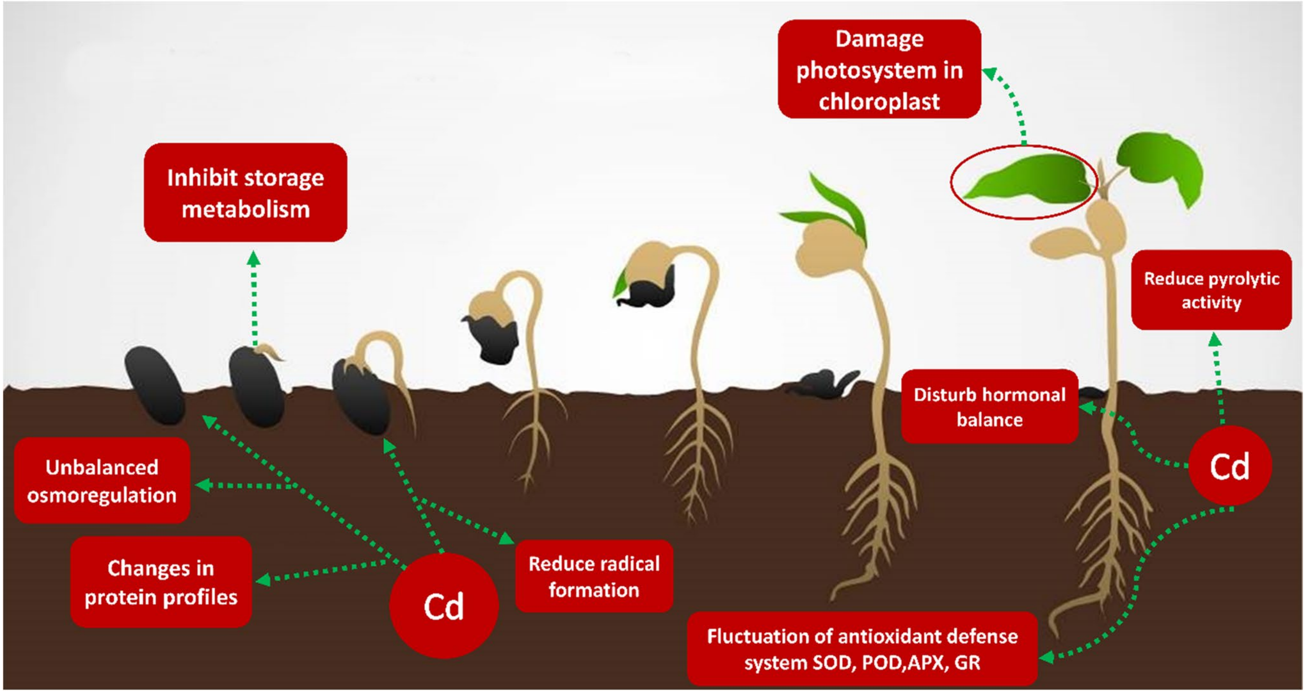

**Fig. 3** Possible interference mechanisms of Cd on seed germination process. Cadmium (Cd) negatively affects metabolic reactivation by reducing levels of hydrolyzing enzymes, starch mobilization and seed imbibition. SOD: superoxide dismutase, POD: peroxidase, APX: ascorbate peroxidase, GR: glutathione reductase. (Conceived from Huybrechts et al. 2019)

cellular, molecular and biochemical alterations, affecting plant morphology as well as physiology (Shanmugaraj et al. 2013; Song et al. 2017). Cadmium-induced retardation and abnormalities of general growth and biomass are linked to several metabolic changes in plants, resulting in inhibited photosynthesis and nitrogen fixation as well as assimilation (Chang et al. 2013; Sebastian and Prasad 2015a; 2015b) which lead to reduced carbohydrate and protein turnover; hence, causes reduction in plant growth. Moreover, Cd stress impairs several cellular activities including inhibited mitotic index and micronucleus formation (Fusconi et al. 2006; Seth et al. 2008), chromosomal abnormalities (Nefic et al. 2013), cell wall lignification (Vaculik et al. 2012), and DNA damages (Seth et al. 2008); eventually, inducing cell death (Zhang et al. 2015a) and growth deformation including necrosis, chlorosis and rolling of leaves, brown, twisted, rigid and mucilaginous roots and stunted growth (Wahid et al. 2008; Lux et al. 2010; Chang et al. 2013; Rizwan et al. 2017; Zhang et al. 2019). Huang et al. (2015) investigated the effect of Cd stress on root morphology of three pepper cultivars (two low-Cd cultivars and one high-Cd cultivar) and reported that under hydroponic conditions, 10 µM concentration of Cd caused a substantial reduction in root tips, length as well as whole root area against control. Cadmium stress has also been reported to inhibit the growth of white clover plants due to its noxious effect on nodulation index as well as its ultrastructure, leading to nodule senescence and reduced carbohydrate and protein synthesis (Manier et al. 2009). Hediji et al. (2015) investigated that Cd did not only reduce the plant biomass and growth, but also caused a decline in fruit production of tomato (*Solanum lycopersicum* L.) plants at 20 µM and 100 µM concentration. These results suggest that tomato plants acclimatize during long-term exposure to 20 µM Cd, while 100 µM Cd results in drastic nutritional perturbations leading to fruit set abortion. Similar results have also been reported in potato (*Solanum tuberosum* L.) (Hassan et al. 2016), cabbage (*Brassica oleracea* var. capitate) (Jinadasa et al. 2016), lettuce (*Lactuca sativa* L.) (Monteiro et al. 2009), radish (*Raphanus sativus* L.) (Varalakshmi and Ganeshamurthy 2013), peanut (Zhang et al. 2013a), mustard (Chen et al. 2011), soybean (*Glycine max*) (Wang et al. 2016a, b) and rice (Zhou et al. 2014; Mostofa et al. 2015; Rehman et al. 2015).

Cd-induced toxic effects on germination and crop growth are highly dependent on its concentration and cultivar and differ from species to species, plant growth stage, and duration of metal exposure (Gul et al. 2018). Such as, two pepper cultivars behaved differently regarding Cd accumulation in roots (Xin et al. 2014).

## 2.2 Uptake and Assimilation of Mineral Elements

Cadmium has been reported to impose contrary impacts on the uptake as well as assimilation of nutrients in plants (Li et al. 2016; Ismael et al. 2019; Mourato et al. 2019), leading towards nutrient deficit known as an inducible deficiency (Khan et al. 2015a). Under the stressed condition, the inhibition in the absorption of essential elements might be ascribed to the competition for root uptake between Cd and mineral elements (Rizwan et al. 2016a, b; Ertani et al. 2017). Primarily, Cd enters the roots via three pathways, generally followed by mineral nutrients, including passive transport in the epidermal layer at the plasma membrane in exchange of $H^+$ (Yamaguchi et al. 2011), through specific ion transporters (Sadana et al. 2003) and specific proteins in the form of chelates (Curie et al. 2009). Furthermore, divalent cation ($Cd^{2+}$) is the principal elemental state of Cd to enter the plants (Song et al. 2016); thereby, competing with other cations. Besides competing for entry, Cd also retards nutrient translocation to aerial plant parts by challenging and inhibiting numerous transporters that are engaged with the nutrient translocation (Wang et al. 2016a, b; Sarwar et al. 2017; Mitani-Ueno et al. 2018; Naeem et al. 2019), genetically interfering with specific transporter gene expression (Migocka and Klobus 2007) and inducing efflux of mineral nutrients from roots (Kovacik et al. 2006). Cd is reported to interfere with several macro as well as microelements such as Zn, Mn, Fe, phosphorus (P), nitrogen (N), and so forth (Solti et al. 2011; Bertoli et al. 2012; Jinadasa et al. 2016; Khan et al. 2016a); hence, disturbing their assimilation and specific role in plants (Sipos et al. 2013). The unfavorable impacts of Cd on the depleted nutrient contents have been observed in several plant species, such as rice (Li et al. 2012a, b), wild garlic (*Allium ursinum* L.) (Street et al. 2010), and soybean (Zhi et al. 2015). Nada et al. (2007) examined the Cd-nutrient interactions and their subsequent impacts on sunflower plants. Cd-induced imbalance in uptake as well as translocation of essential elements in plant tissues; resulting, depletion of Fe and Mn in leaves. Moreover, Fe deficiency also caused a reduction in chlorophyll as well as ferredoxin content in the plant, resulting, in inhibited photosynthesis and other metabolic processes. Khan et al. (2016b) investigated the Cd interaction with primary macronutrients and found that Cd application (1, 2.5, and 5 mg $kg^{-1}$) reduced that N content in tomato plants by 70, 9, and 34% corresponding; while, reduction in P as well as potassium (K) content was also observed in tomato and potato plants. Astolfi et al. (2005) detected inhibitory impact of Cd on $H^+$ATPase in maize, which is a cytoplasmic-membrane-associated metal-sensitive enzyme system, controlling transport of ions across the membrane.

Phytotoxicity induced by Cd has also been reported to pose deleterious effects on N metabolism including N uptake, fixation as well as assimilation by inhibiting the action of enzymes associated with N metabolic pathway (Chang et al. 2013), thus inducing physiological changes which result in restricted plant growth (Shanmugaraj et al. 2019). Karina et al. (2003) studied the N metabolism of soybean plants exposed to two distinctive Cd concentrations (50 and 200 µM). At 200 µM concentration, reduced nodulation and inhibited the action of nitrogenase was detected in plants, resulting impaired N fixation as well as ammonia assimilation. Similar results have also been observed in mung bean (Cd 20 mg $kg^{-1}$) (Wahid et al. 2007), chickpea (Cd 50, 100, or 150 µM) (Hasan et al. 2008) and white lupin (*Lupinus albus* L.) (Sanchez-Pardo et al. 2013). Furthermore, Cd is documented to disturb $NO_3$ assimilation in plants by diminishing the action of nitrate reductase, a key enzyme involved in $NO_3$ assimilation by catalyzing the NAD(P)H reduction of $NO_3$ to $NO_2$ (Singh et al. 2019) and increasing in the endogenous NO concentration in different plant species (Valentovicova et al. 2010).

The impact of Cd exposure on plant nutritional status is highly dose-dependent which differs by changing the Cd exposure time, cultural medium, and varies among different species, genotypes, and cultivars (Naeem et al. 2019). For instance, Hediji et al. (2015) reported varied calcium (Ca) content in tomato plants when subjected to different Cd (20 µM and 100 µM) concentrations. It was observed that Cd interacted synergistically as well as antagonistically with mineral contents at 20 µM and 100 µM concentration, correspondingly. Cd stress reduced Ca, Cu and Zn contents in shoots and increased them in roots. High Cd level led to a significant decrease in K and Mg content in all plant organs. Furthermore, Fe concentration was reduced in roots, stems, and leaves but increased in flowers, seeds, and red ripe fruits. Similarly, a positive correlation between Cd and mineral elements was reported when welsh onion (*Allium fistulosum*) L. was exposed to different Cd concentrations (Li et al. 2016). Goncalves et al. (2009a) explored the impact of Cd on the nutritional status of potato in hydroponic as well as in-vitro experimental conditions and reported that Cd impact on plant nutrient content is dependent on the experimental cultural medium, as Cd-induced no effect on the plant nutritional status in a hydroponic culture; while, in case of in-vitro conditions, the essential elements including Ca, K, Mg, Zn, Mn, Fe, and copper (Cu) diminished in both the roots as well as shoot.

Although, the Cd-nutrient interactions are well known in diverse plant species; however, the mechanism of these interactions is still unclear which needs further investigation. Besides, most of the existing research regarding the assessment of Cd effects on plant nutritional status is associated with the spiking of plant growing medium, i.e., soil or hydroponic culture with Cd, which may not be completely illustrative of natural field condition (Khan et al. 2016a). For that reason, to fill this literature gap, more extensive field research is needed to be explored to assess these impacts under natural conditions.

## 2.3 Plant Water Relations

In response to Cd exposure, plants are subjected to varying degrees of water stress, due to several morphological as well as physiological alterations including decreased intracellular space, cell size, number, and diameter of vascular bundles (Fernandez et al. 2013). These modifications result in disrupting the plant ionic homeostasis by inducing changes in plasma membrane permeability; thus, inhibiting the stomatal conductance, transpiration rate, and relative leaf water content (Domınguez et al. 2011). According to Thevenod and Lee (2013) Cd induces irregularities in signal transduction as well as stomatal gas exchange in response of its antagonistic effect on Ca and K levels in plants, respectively. It is reported to interfere with Ca metabolism due to its competitive behavior to get entry in guard cells through Ca channels which results in aberrant signal transmission; consequently, guard cells become flaccid. (Corguinha et al. 2012). Moreover, Cd toxicity causes a substantial decline in the hydraulic conductivity by reducing the root surface area as well as root hair density for water absorption (Gouia et al. 2003). If soils are Cd contaminated, the soil solution's osmotic ability may be lower than that of root cell sap (Małecka et al. 2008). Under such conditions, soil solution will severely limit plant water absorption levels and result in osmotic pressure (Rucínska-Sobkowiak 2016).

Disturbance in the water status of plants under Cd exposure is reported in a variety of crops. Nedjimi and Daoud (2009) demonstrated the effect of excessive Cd concentration on the nutritional and water status of saltbush (*Atriplex halimus*). It was reported that Cd drastically abridged K and Ca content in both roots as well as shoot, caused a significant reduction in transpiration and hydraulic conductivity: thus, the roots and shoot were characterized by decreased water content in the tissues. Similarly, *Sedum alfredii* (Crassulaceae) when exposed to 600 µM Cd, the leaf water content considerably reduced to 0.69% as compared to control owing to restrained root development; hence, water uptake and supply to shoot is disturbed (Zhou and Qiu, 2005). Polle et al. (2013) observed Cd-induced water stress in euphrates poplar (*Populus euphratica*) and found it in a wilting state due to fluctuation in turgor pressure and turgidity loss by guard cells. Likewise, euphrates poplar when exposed to Cd (50 µM), displayed significant contraction of cytoplasm, resulting impaired ionic homeostasis and water balance (Sun et al. 2013). In this scenario, plant growth inhibition is further aggravated due to the hampered rate of transpiration as well as nutrient translocation from one part to another (Sipos et al. 2013). Cadmium-induced hindrance of stomatal conductance has also been stated in numerous plant species including white clover (*Trifolium repens)*, evergreen oak (*Quercus ilex)*, rice, *Picris divaricate,* and soybean (Ying et al. 2010; Dominguez et al. 2011).

During the course of evolution, plants have evolved intricate strategies to cope with Cd-induced stress by enhanced accumulation of osmolytes (El-Esawi et al. 2020). Plants under Cd stress are found to reflect escalated levels of abscisic acid (ABA) a phytohormone involved in stomatal closure, resulting diminished respiratory rate (Roelfsema and Hedrich 2005). However, in response to Cd stress, plants show adaptive behavior by synthesizing a higher concentration of osmolytes such as proline to maintain osmotic balance (Yakhin et al. 2009) which is also an indicator of stressed condition (Tran and Popova 2013). Tobacco (*Nicotiana tabacum* L.) plants exhibited antioxidant response against Cd exposure by accumulating a greater concentration of proline in cells to assuage Cd toxicity (Islam et al. 2009). In an experiment, it was observed that increase in Cd concentration reduced the leaf water potential in mustard; whereas with increase in Cd concentration, the leaf proline level also increased and protected the plant growth and restricted the uptake and transport of Cd (Irfan et al. 2014). Similarly, in another study Cd and other heavy metals induced stress triggered the accumulation of osmolytes such as sucrose, mannitol and glycine betaine (Dhir et al. 2012).

## 2.4 Enzymatic Activity

Cadmium is accounted to have a well-marked deterrent impact on the functional capabilities of numerous principle enzymes in plants owing to its exorbitant binding affinity with sulfanyl functional group (-SH) on them and competition for replacing enzyme activating cations including Zn, Mg and Ca (Cuypers et al. 2011; Pourrut et al. 2011; Gupta et al. 2019). In roots, it is reported to interfere with plasmalemma associated $H^+$ATPase, which maintains electrochemical gradient and behaves as a proton pump by providing the driving force for nutrient uptake as well as transportation (Falhof et al. 2016); thus, leading to restricted root activities (Astolfi et al. 2005). Skrebsky et al. (2008) examined the effect of Cd (0, 20, 40, 60, and 80 µM) on acid phosphatase (ACP) and δ-aminolevulinic acid dehydratase (ALA-D) activities in *Pfaffia glomerata* plants which are involved in maintaining P status and biosynthesis of photosynthetic pigments, respectively. Cadmium detained the ALA-D activity by 89% at 80 µM Cd concentration. While, up to 23% and 30% inactivity in ACP was observed in the shoot as well as root, respectively, which might be due to Cd interference with $PO_4^{3-}$ binding sites or replacing ACP activating $Ca^{2+}$ and $Mg^{2+}$ ions. Similarly, upon Cd exposure (200 µM), soybean plants experienced 100% arrest in ALA-D activity in roots and leaves, while 72% retardation was noted in nodules. Moreover, Cd inhibited ALA-D activity enhanced ALA accumulation in roots (2.5-fold), leaves (104%), and nodules (46%) which caused oxidative stress by triggering enhanced ROS formation in plants (Noriega et al. 2007).

Seedling growth facilitating enzymes are potentially inactivated under Cd induced stress (Yan et al. 2014). Significant physiological inhibition of proteases and α-amylases and acid phosphatases (ACPs) was observed in barley seeds which catalyze the sugar reserves mobilization in the endosperm (Kalai et al. 2014). Salas et al. (2018) observed proteolytic enzyme alteration in rice due to Cd stress which is involved in metabolic activities by hydrolyzing the protein substrates. Up to 50% inactivation was observed in leucine aminopeptidase; while, carboxypeptidase activity was contrarily enhanced which catalyze the hydrolysis of leucine and arginine into lysine substrates, respectively.

In addition, Cd is reported to adversely affect the plant N metabolism by hampering the activity of enzymes related to N uptake as well as fixation (Chang et al. 2013). Cd is documented to reduce nitrogenase activity, playing a vital role in N fixation, in various plant species such as *mungbean* (Wahid et al. 2007) and chickpea (Hasan et al. 2008). Moreover, activities of some other enzymes involved in the plant $NH_4^+$ assimilation are also hampered upon Cd exposure, resulting in N deficiency (Sanchez-Pardo et al. 2013).

Conversely, Cd-induced intensification in some enzyme activities is also exhibited. McCarthy et al. (2001) reported that Cd positively affected the activities of leucine-aminopeptidase, endopeptidase isozymes, and glyoxylate cycle enzymes in peas which exhibited senescence symptoms on leaves. Likewise, activities of arginine decarboxylase and ornithine decarboxylase improved in sunflower plants which negatively affected antioxidant level in plants (Groppa et al. 2008).

## 2.5 Ultra-structural and Oxidative Damages

Cd prompted oxidative stress is accounted in plants owing to the escalated generation of reactive oxygen species (ROS) (Andresen and Küpper 2013; Ehsan et al. 2014a; Gutsch et al. 2019), suppressed antioxidant system (Abbas et al. 2017), and redox imbalance (Petrov et al. 2015); ultimately, causing oxidative impairment as well as lipid peroxidation (Younis et al. 2016). Being a non-redox element, Cd is reported to generate ROS including superoxide anion ($O_2^-$) singlet oxygen ($1O_2$), hydrogen peroxide ($H_2O_2$), or hydroxyl radicals ($OH^-$) via indirect pathways (Iannone et al. 2010; Fig. 4). For instance, Cuypers et al. (2011) reported that the high affinity of Cd for Carboxyl (-COOH), thiol (-SH), and histidyl groups on antioxidant enzymes are responsible for oxidative stress, as it tends to inactivate the antioxidative defense system which results in shattering of ROS balance; ultimately, leading towards plant growth inhibition

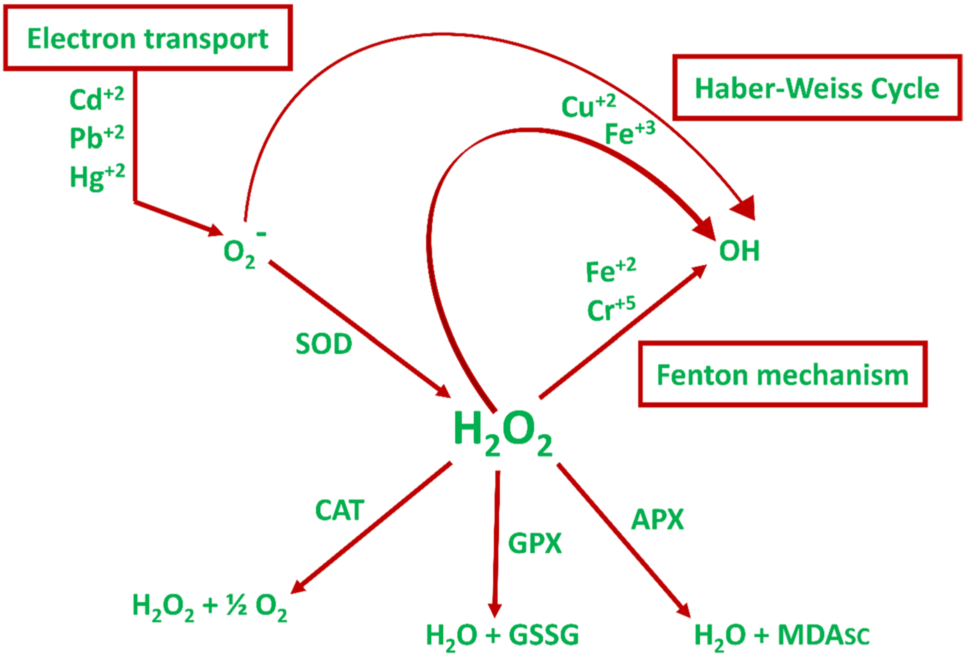

**Fig. 4** Effect of cadmium on generation of reactive oxygen species and activities of antioxidant enzymes. The intoxication with pollutant metals induces oxidative stress because they are involved in several different types of ROS-generating mechanisms. For example, transition metals (such as $Fe^{3+}$ and $Cu^{2+}$) participate in the Haber–Weiss cycle, producing OH from $O_2^-$ and $H_2O_2$. Metals without redox capacity (such as $Cd^{2+}$, $Pb^{2+}$, and $Hg^{2+}$) can enhance the pro-oxidant status by reducing the antioxidant glutathione (GSH) pool, activating calcium-dependent systems and affecting iron-mediated processes. These heavy metals also disrupt the photosynthetic electron chain, leading to $O_2^-$ and $^1O_2$ production. CAT: catalase, SOD: superoxide dismutase, GPX: guaiacol peroxidase, APX: ascorbate peroxidase, GSSG: reduced glutathione, MDA: malondialdehyde ( Modified from Benavides et al. 2005)

(Sebastian and Prasad 2013). In the cytosol, Cd instigates phospholipases, which brings about the cellular release of linolenic acids, acting as derivatives for lipoxygenase or ROS formation (Belkadhi et al. 2015).

In addition, Cd indirectly generates ROS by disrupting the ultra-cellular components such as peroxisomes, chloroplasts, and mitochondria which are considered as fundamental ROS generating points in plants (Pietrini et al. 2003; Lushchak 2011). Cysteine residues, Fe–S clusters, thiol and binding sites for divalent metals are potential Cd target sites, leading to electron transport chain inhibition, proton motive force dissipation, and cell dysfunction (Kurochkin et al. 2011). According to Heyno et al. (2008), blockage of the mitochondrial electron transport system is the principal target of Cd to induce free radicals. Additionally, malfunctioning of metalloproteins in photosynthetic as well as mitochondrial electron transport chains is also liable to induce ROS subjected to Cd stress (Belyaeva et al. 2012; Parmar et al. 2013). Furthermore, NADPH oxidase concomitant ROS generation is another proposed mechanism for Cd-induced oxidative damage (Gill and Tuteja 2010). Cd promotes the activity of plasmalemma associated NADPH oxidase which results in catalyzing $O_2$ reduction reaction by making use of NADPH as a reducing agent; eventually, the formation of superoxide ($O_2^-$) free radical (Chou et al. 2012). Similar observations are also documented in pea (Rodriguez-Serrano et al. 2006), tobacco (Olmos et al. 2003; Garnier et al. 2006), and black nightshade (*Solanum nigrum*) (Deng et al. 2010).

Ultra-structural damages including protein oxidation, enzyme inhibition, membrane lipid peroxidation (Popova et al. 2009), ionic leakage (Goncalves et al. 2007), and DNA as well as RNA destruction are the manifestation of plant oxidative stress; eventually, leading to hampered activities of cellular organelles and plant death (Shahid et al. 2014c; Gratao et al. 2015). Lipid peroxidation is involved in rupturing of bio-membrane in Cd stressed plants (Andresen and Küpper 2013; Liptakova et al. 2013) which ultimately results in physiological dis-functioning of cellular ultra-structures such as glyoxisomes, peroxisomes, mitochondria, and chloroplast (Keunen et al. 2011). Ali et al. (2013c) found morphologically impaired mitochondria, cracked cell walls, and plasmolysis in Cd stress rapeseed plants. Similar results are also observed in cotton (*Gossypium hirsutum* L.) (Daud et al. 2009) and *Sedum alfredii* (Jin et al. 2008). Furthermore, it is reported to cause peroxisome senescence, and its prompted metabolic alteration to glyoxisomes (McCarthy et al. 2001).

Genotoxicity is another outcome of Cd-induced oxidative stress in plants which is associated with ROS imbalance resulting in lipid peroxidation and generating mutagenic aldehydes (Lin et al. 2015). According to Kranner and

Colville (2011) due to the electrophilic nature of $OH^-$ free radical, it is highly inclined to oxidize DNA by interfering with nitrogenous foundations and can modify 100000 s of purine as well pyrimidine bases per cell within a day. Preferentially, $OH^-$ radical is reported to target position 5 of pyrimidine bases i.e. cytosine (C) and thymine (T), and results in the formation of allylic radicals by attacking H atom in thymine methyl groups; which in turn, produce protonation inducing peroxyl radicals (Nzengue et al. 2015). Moreover, Cd prompted lipid peroxidation also results in DNA damage owing to the ability of its by-products such as 4-hydroxy-2-nonenal as well as malondialdehyde (MDA) to interact with nucleotide bases (Stone et al. 1990). Furthermore, Cd-stimulated ROS shuttling is also responsible for mitotic impairments via micronucleus formation and chromosomal aberrations (Circu and Aw 2010). Foltete et al. (2012) reported emanated micronuclei frequency in Cd exposed (510 µM $CdCl_2$) *Vicia faba* plants. In another study, random amplified polymorphic DNA (RAPD) indicators of Cd exposed plants were observed which showed deviations in DNA band intensity (Liu et al. 2005). Similar observations are also documented in various plant species such as tobacco and onion (*Allium cepa*) (Bandyopadhyay and Mukherjee 2011).

## 2.6 Changes in Antioxidant Defense System and Stress Protein

In light of Cd-stimulated oxidative stress, plants are well known to develop defensive system against ROS (Horvath et al. 2007) including both enzymatic antioxidants such as ascorbate peroxidase (APX), catalase (CAT), glutathione peroxidase (GPX), peroxidase (POD), glutathione reductase (GR), dehydroascorbate reductase (DHAR), superoxide dismutase (SOD), monodehydroascorbate reductase (MDHAR), glutathione-S-transferases (GST), and non-enzymatic scavengers such as glutathione (GSH), ascorbic acid, carotenoids, tocopherols, phytochelatins, and thiols as well as phenolic compounds (Shanthala et al. 2006). These free radical scavengers make an imperative defensive system counter to Cd phytotoxicity (Iqbal et al. 2010) by behaving as reducing agents which tend to convert ROS into innocuous end products (Table 1; Shahid et al. 2014c; Abbas et al. 2015). Moreover, activation of these antioxidant enzymes has been reported due to variations in gene regulation (Anjum et al. 2012) and an increase in their substrate content under metal stress (Anjum et al. 2012). Shamsi et al. (2008) evaluated enhanced SOD, as well as POD activities and higher MDA content in Cd, stressed soybean plants. Agrawal and Mishra (2009) investigated the influence of Cd (68 µM) on lipid peroxidation (LPO) and enzymatic as well as non-enzymatic antioxidants in pea plants and found a substantial decrease in CAT activity and ASA content; whereas, a contrary effect was detected for SOD, POD. Moreover, higher content of non-enzymatic ROS scavengers including proline, flavonoids, and thiols was observed due to enhanced lipid peroxidation. Phytochelatin production has also been reported as an antioxidant response of plants counter to Cd stress (Cabala et al. 2011). Jinadasa et al. (2016) evaluated the impact of Cd toxicity (500 µg $L^{-1}$) on cabbage and reported enhanced phytochelatin formation in shoot and roots as compared to control. In another study, Cd-induced (5 µM $CdCl_2$) oxidative stress was detected in pea plants, as evidenced by enhanced MDA and non-protein thiol content and escalated activity of chitinase, CAT, and POD (Metwally et al. 2005). Likewise, mustard plants exhibited higher activities of MDHAR and DHAR upon 10 µM Cd exposure (Markovska et al. 2009). Comparable results have also been reported in diverse plant species like mustard (Hayat et al. 2007; Irfan et al. 2014), sunflower (Saidi et al. 2014), rapeseed (Ehsan et al. 2014a), common bean (*Phaseolus vulgaris* L.) (Saidi et al. 2013; Howladar 2014), wheat (Agami and Mohamed 2013; Chen et al. 2014a), cotton (Farooq et al. 2013), tomato (Monteiro et al. 2011) and chickpea (Hasan et al. 2007).

Although, Cd stress induces an antioxidant defense system in plants, however, several studies have observed variations in responses to ROS scavengers depending upon the Cd concentration, genotypes, plant species, physiological plant conditions, and tissue specificity (Srivastava et al. 2014; Hussain et al. 2019). Ali et al. (2002) evaluated the effect of a concentration series of Cd on the antioxidant system of rice seedlings and found fluctuations in antioxidant concentrations at varying Cd levels. An increasing trend was observed with SOD and GR in both roots and leaves; while, APX and POD showed a concentration-dependent contrasting trend, by increasing as well as decreasing their activity in response to low and high Cd concentrations, respectively. Moreover, in case of CAT, tissue-dependent high activity was observed in roots; whereas, its activity declined in leaves. A similar trend in antioxidant activities is observed in Cd stressed rapeseed (Yan et al. 2015). Molina et al. (2008) unveiled the variable and tissue-specific response of antioxidative defense in mung bean seedlings exposed to 40 µM Cd concentration. Cadmium imposed a negative effect on CAT and GSSH concentration; whereas SOD and GPX activities improved in leaves, but a contrasting pattern was observed in roots. In another study in Cd-treated rice, GST activity was reported to rise in the shoot; however, the opposite pattern was observed in roots (Zhang and Ge 2008). Furthermore, antioxidant enzyme activity has been found to fluctuate in different plant species. For instance, under Cd-induced oxidative stress, ASH content enhanced in barley; while its concentration reduced in soybean, cucumber (*Cucumis sativus* L.), and pea with no substantial change in *Populus canescens* (Gill and Tuteja 2010). Likewise, CAT activity

**Table 1** Effects of Cd toxicity on activities of different antioxidant enzymes and lipid peroxidation in different plants

| Plant species | Enzymes | | Culture | Cd exposure level | Cd exposure duration (d) | References |
|---|---|---|---|---|---|---|
| | Increased | Decreased | | | | |
| *Arabidopsis thaliana* | SOD, AsA, CAT | GSH | Hydroponic | 0, 5, 10 µM | 0, 2, 24, 48 and 72 h | Jozefczak et al. (2014) |
| Tomato | CAT, GR, GPOX, APX | | Soil | 0 and 1 mM | 47 | Gratao et al. (2015) |
| Strawberry (*Fragaria x ananassa* cv. Camarosa) | SOD, CAT | APX | Soil | 0, 15, 30, 45 and 60 mg kg$^{-1}$ | | Muradoglu et al. (2015) |
| Corkscrew willow (*Salix matsudana*) | SOD, CAT, APX | | Soil | 150 µM | 30 | Yang et al. (2015a) |
| Poplar (*Populus yunnanensis*) | APX, CAT, GR, SOD | | Soil | 100 µM | 0, 4, 8, 12 | Yang et al. (2015b) |
| Highbush blueberry (*Vaccinium corymbosum* L.) | SOD | | Hydroponic | 50, and 100 µM | 7, 14, 21 | Manquián-Cerda et al. (2016) |
| Sorghum (*Sorghum bicolor*) | GST | | Hydroponic | 0, 100, and 150 µM | 5 | Roy et al. (2016) |
| Nettle (*Urtica dioica* L.) | GR, GST, | | Hydroponic | 0, 0.045, and 0.09 mM | 58 | Tarhan and Kavakcioglu (2016) |
| Date palm (*Phoenix dactylifera* L.) | CAT, SOD | | Soil | 300, 600, and 900 µM | 90 | Al-Qurainy et al. (2017) |
| Spinach | CAT, GR, GPOD | | Hydroponic | 25 µM | 1, 2, 7 | Pinto et al. (2017) |
| Candle bush (*Cassia alata*) | CAT, APX, GPX, GSH | | Hydroponic | 0, 22, 44, 88, and 132 µM | 30 | Silva et al. (2017) |
| Hyacinth bean (*Dolichos lablab* L) | CAT, APX, GR | GPOX | Soil | 0, 50, 100, and 200 µM | 5 | Souza et al. (2017) |
| Parsley (*Petroselinum hortense* L.) | SOD | CAT, APX | Soil | 0, 75, 150 and 300 µM | 15 | Ulusu et al. (2017) |
| Bermuda grass (*Cynodon dactylon*) | CAT, SOD, POD, GR | | Soil | 750 mg kg$^{-1}$ | 21 | Shi et al. (2014) |
| Indian bassia (*Bassia indica*) | SOD, CAT, POD, APX, GR, PPO | | Peat and sand at 1:1 ratio | 150 µM | | Hashem et al. (2016) |
| Chinese cabbage (*Brassica rapa* L.) | SOD, CAT, POD, AsA, GSH | | Hydroponic | 50 µM | 2 | Zong et al. (2017a) |
| Chinese cabbage | SOD, CAT, POX | | Hydroponic | 50 µM | 7 | Zong et al. (2017b) |
| Rapeseed | GR, GPX, GSH | | Soil | 50 and 100 mg kg$^{-1}$ | 15 | Anjum et al. (2014) |
| Mung bean | GSH, GR | GPX, GST | Pot | 50 and 100 mg kg$^{-1}$ | 15 | Anjum et al. (2014) |
| Wheat | CAT | | Hydroponic | 220 mg kg$^{-1}$ | 7 | Baruah et al. (2019) |
| Tomato | CAT | | Hydroponic | 220 mg kg$^{-1}$ | 7 | Baruah et al. (2019) |
| Pea | CAT | | Hydroponic | 220 mg kg$^{-1}$ | 7 | Baruah et al. (2019) |

*AsA* ascorbic acid, *APX* ascorbate peroxidase, *CAT* catalase, *GPX* glutathione peroxidase, *POD* peroxidase, *GR* glutathione reductase, *DHAR* dehydroascorbate reductase, *SOD* superoxide dismutase, *MDHAR* monodehydroascorbate reductase, *GST* glutathione-S-transferases, *GSH* reduced glutathione, *PPO* polyphenol oxidase, *GPOX* guaiacol peroxidases

is stated to decline in common reed (*Phragmites australis*) and bell pepper (*Capsicum annuum*); while enhanced activity is observed in rice, wheat, black bean, mustard and chickpea (Gill and Tuteja 2010). A similar trend with POD activity was observed in radish and pea plants (El-Beltagi et al. 2010).

Moreover, Cd stress also brings alterations in the plant protein pool due to mutations in gene expression (Tran and Popova 2013). It upregulates several stress proteins like HSPs (heat shock proteins), proteinases, and pathogenesis-related proteins to resist metal-induced stress in plants; whereas proteins associated with plant primary metabolisms such as Calvin cycle, glycolysis, and Krebs cycle are strikingly downregulated (Kieffer et al. 2009). In rice, Cd treatment led to interruption in the synthesis of 36 proteins. In aerial plant parts, 16 proteins were upregulated; while 3 proteins were downregulated. However, in case of roots, quantitative increase and decrease in protein biosynthesis were 16 and 1, respectively (Lee et al. 2010). Rodriguez-Celma et al. (2010) investigated that Cd-induced alterations in plant protein metabolism are dose-dependent. It was observed that two different Cd concentrations i.e. 10 µM and 100 µM caused alterations in 36 and 41 polypeptides, correspondingly. Semane et al. (2010) reported upregulation of 21 proteins in *Arabidopsis thaliana*, treated with 10 µM Cd. Similarly, Rodriguez-Serrano et al. (2009) found Cd-induced production of PrP4A and HSP71: pathogen-associated proteins in pea plants, which were upregulated in the plant's defensive response against Cd stress. Plant defensive response was also observed in Cd-treated wheat seedlings, where a 51-kDa stress-associated protein was detected in root tissues (Mittra et al. 2008).

## 2.7 Carbon Metabolism and Yield Formation

Retardation of plant carbon metabolism including photosynthesis as well as respiration is the well-known expression of Cd toxicity, leading towards yield loss. Cd has been reported to inhibit photosynthesis via several direct as well indirect means, such as a reduction in expression of photosynthesis associated genes including psbA rbcL and psaB (Qian et al. 2010), lipid peroxidation (Iannone et al. 2010), disturbed nutrient metabolism (Qureshi et al. 2010) and augmented proteolysis (Pena et al. 2007); resulting, structural as well functional damages to photosynthetic machinery (Parmar et al. 2013). According to Najeeb et al. (2011) Cd toxicity (100 µM) inhibits C-fixation by giving marked distortion to the entire photosynthetic machinery, causing disturbed and inflated thylakoids, hence damage to both light as well as dark reaction centers. However, the light reaction center of chloroplast comprising photosystem I (PSI), photosystem II (PSII), and antenna complex is more affected, especially PSII (Kupper et al. 2007). Cd stress remarkably impaired the activity of PSII over short duration of exposure to *Thlaspi caerulescens* (Kupper et al. 2007); whereas, over a long exposure period, activities of both photosystems arrested in pea (Goussi et al. 2018). Prasad et al. (2004) suggested that a greater impairment of PSII activity in comparison with PSI might be linked with greater activity of ROS at PSII. Moreover, disruption of photosynthetic apparatus is also attributed to enhanced lipid peroxidation under Cd stress due to augmented activity of lipoxygenase (LOX) (Cuypers et al. 2010). Under Cd stress, lipid peroxidation in association with LOX activity has been detected in various plant species like Lupine, Arabidopsis, Phaseolus, and Barley (Maksymiec and Krupa 2006; Tamas et al. 2009). Besides, Cd inhibited photosynthesis may be ascribed to disorganization of both electron acceptor as well as donor sides of PSII; hence, averting photoactivation (Sigfridsson et al. 2004). On the donating side, Cd replaces Ca in Ca/Mn cofactor for enzymatic activities at oxygen-evolving complex (OEC) (Dinakar et al. 2009); while, on the other side, it retards the $e^-$ conductance due to configurational modification of primary as well as secondary acceptor quinone (Geiken et al. 1998).

Biosynthetic retardation of light-capturing pigments such as chlorophyll, neoxanthin, lutein, violaxanthin, and carotenoids is another mechanism of photosynthetic inhibition (Wan et al. 2012; Chang et al. 2013; Xue et al. 2014). Cd has been stated to interfere with δ-aminolevulinic acid (ALA) dehydratase (Mysliwa-Kurdziel and Strzalka 2002; Sharma et al. 2020), porphobilinogen deaminase (Skrebsky et al. 2008), and protochlorophyllide reductase (Stobart et al. 1985), key enzymes in chlorophyll biosynthesis pathway; resulting, the diminished raw material for photosynthetic pigments (Goncalves et al. 2009b). Similar observations are documented in several plant species such as cucumber, tomato, and spinach (*Spinace oleracea*) (Goncalves et al. 2009b; Lopez-Millan et al. 2009; Hediji et al. 2010). Moreover, because of the resemblance of UV visible absorption spectrum, Cd substitutes Mg in both, chlorophyll a as well as b (Gillet et al. 2006). However, Cd substituted chlorophyll pigment is unfit for photosynthesis, as all absorbed energy is dissipated in the form of heat due to unstable excited state (Kupper et al. 2006).

In addition, Cd acts as a potent suppressant of the Calvin cycle by impairing the vital enzymatic activities; consequently, hampering C-fixation (Bashir et al. 2013; Song et al. 2019). Cd has been reported to target several $CO_2$ assimilating enzymes including ribulose-1,5-biphosphate carboxylase (RuBPCase), phosphoenolpyruvate carboxylase (PEPCase), aldolase, phosphofructokinase, fructose-1,6-bisphosphatase, NADP-dependent glyceraldehyde-3-phosphate dehydrogenase, and carbonic anhydrase (Song et al. 2019). Song et al. 2019 reported hampered Rubisco activity in sunflower plants which resulted in abridged quantum efficiency of PSII and $CO_2$ assimilation.

Among respiratory activities, Cd is reported to obstruct leaf respiration due to its interference with stomatal conductance through its entry into guard cells by competing with Ca (Pietrini et al. 2010; Souza et al. 2011), leading towards stomatal closure and abridged stomatal density (Deng et al. 2014), which subsequently results in overall obstruction of $CO_2$ assimilation. Moreover, mitochondrial respiratory activities are also impeded due to Cd interference with the Krebs cycle (Bezawork-Geleta et al. 2017) as well as $O_2$ evolving $e^-$ transport chain (Branca et al. 2020). Cadmium is reported to induce changes in the activities of several respiratory enzymes (Shanying et al. 2017) such as malate dehydrogenase, succinate cytochrome c reductases, nicotinamide adenine dinucleotide (NADH), succinate dehydrogenases, cytochrome c oxidase, phosphogluconate dehydrogenases, and alcohol dehydrogenase; thereby, retarding pant C metabolism (Smiri et al. 2009). Nevertheless, to the best of our knowledge, several literature gaps regarding the impact of Cd on respiratory activities remain to be addressed. All of the prior studies about respiration are based on Cd impact on stomatal conductance; while respiratory activities in relation to roots and mitochondrial respiratory activities are still not presented in the literature. Furthermore, Cd exposure primarily disturbs the RuBP carboxylase activity, while Cd relation to its oxygenase activity needs to be investigated.

Cadmium is a potentially toxic pollutant that induces diverse metabolic alterations in the plant body leading towards yield loss (Table 2). Wani et al. (2007b) reported 40% reduction in seed yield when gram plants were subjected 24 mg kg$^{-1}$ Cd concentration. However, the impact of Cd toxicity on crop yield varies among different genotypes (Huang et al. 2017). Huang et al. (2008) assessed the yield loss in various Cd stressed rice genotypes. It was found that Cd tolerant genotypes exhibited up to 9% significant reductions in yield in comparison to Cd susceptible genotypes, for which, about 50% loss in yield was reported. Furthermore, Chen et al. (2014b) observed the response of cotton plant to different Cd concentrations regarding yield and found contrary results. Low Cd concentration, improved plant growth and development, while plant growth, lint yield, boll number per plant, and boll weight significantly reduced under high Cd concentration. Similarly, Li et al. (2011) indicated a significant decline in pod number per plant, size of cotton bolls, seed cotton, and lint yield under Cd stress. In case of wheat, a significant decline in spikelet number, grain number per spike, and 1000-grain weight were detected in plants, exposed to Cd toxicity (Yang et al. 2011). Moreover, similar outcomes are also documented in other crops including corn (Cao et al. 2005a, b), mung bean (Wani et al. 2007b), and rapeseed (Yuan and Sun 2014). In sum, Cd toxicity hampered the crop yield and yield-related traits substantially.

**Table 2** Effect of Cd stress on yield of some representative field crops

| Crop species | Cd level | Yield reduction (%) | Reference |
|---|---|---|---|
| Rice | 150 ppm | 38.33 | Huang et al. (2008) |
| Rice | 150 ppm | 42.13 | Huang et al. (2008) |
| Peanut | 15 ppm | 16.98 | Fang et al. (2012) |
| Cotton | 400 µM | 23.79 | Chen et al. (2014b) |
| Pea | 68 µM | 16.38 | Agrawal and Mishra (2009) |
| Radish | 200 ppm | 45.09 | Varalakshmi and Ganeshamurthy, (2013) |
| Rice | 14.7 ppm | 11.30 | Cui et al. (2012) |
| Maize | 375 µM | 6.16 | Anjum et al. (2015) |
| Rice | 150 ppm | 34.37 | Kanu et al. (2017) |
| Wheat | 2.86 ppm | 27.5 | Abbas et al. (2018) |
| Wheat | 10 ppm | 38.07 | Farooq et al. (2020) |
| Tomato | 50 µM | 25.50 | Xie et al. (2021) |

## 3 Cadmium Dynamics in Rhizosphere

Cadmium is an extremely ecotoxic element with its natural concentration in soil ranges from 0.06 to 1.1 ppm with an average concentration of 0.41 ppm (Kabata-Pendias and Pendias 2011). It is present in different bioavailable fractions such as exchangeable fraction, soluble fraction, organically, and inorganically bound fractions, and mineralogical Cd (Mohamed et al 2010). Upon weathering, it readily enters into the soil mobile pool and forms numerous complex compounds with inorganic ions as well as organic substances. In case of its speciation, Cd is reported to exist in several cationic as well as anionic forms in the soil such as $CdCl^+$, $CdHS^+$, $CdHCO_3{}^+$, $CdOH^+$, $Cd(HS)_4{}^{2-}$, $CdCl_3{}^-$, $Cd(OH)_3{}^-$, and $Cd(OH)_4{}^-$ (Kabata-Pendias and Sadurski 2004). In acidic soil, Cd, is present as $CdCl^+$, and $CdSO_4$; (ii) in alkaline soil, $CdHCO_3{}^+$; (iii) in oxic soil, $Cd^{2+}$, and $CdCl^+$ (Kabata-Pendias and Mukherjee 2007). Nonetheless, $Cd^{2+}$ is considered to be the Cd specie that is most available to plants (Taylor and Percival 2001).

## 4 Factors Affecting Cadmium Dynamics

The physico-chemical characteristics of soil including pH, clay particles, redox reactions, charged mineral particles, nature of sorbent, soil nutritional status and root effluxed organic acids are the major factors influencing the Cd mobility as well as bioavailability in soil (Violante et al. 2010; Tomas et al. 2012). Among these, pH is the most crucial aspect influencing Cd behavior in soil (Cotuk et al. 2010). There is a contrasting trend between Cd bioavailability and pH, as its mobility increases by decreasing soil pH with the greatest mobility at 4.5–5.5 pH and vice versa (Jung 2008). Under low soil pH, the mobility and bioavailability of Cd are higher owing to its conversion from precipitated form, i.e., Fe and Mn carbonates and oxides to soluble form (Li et al. 2014a). Redox potential (Eh) is another important factor affecting the Cd concentration and solubility in soil. Cadmium is reported to observe a linear trend with Eh, as its solubility escalates with increased soil Eh which might be ascribed to Cd interaction with dissolved organic C and Mn and precipitations such as sulfides (Frohne et al. 2011). Besides these, soil organic residues pay a significant concern in governing the Cd sorption as well as solubility, as it promptly interacts with Cd to form complexes (Quenea et al. 2009). Soils with higher organic matter have relatively lower Cd uptake by plants owing to Cd-sorption (Shahid et al. 2012). Soil texture also affects the Cd solubility in soil as Andersen et al. (2002) reported higher Cd bioavailability in sandy soil as compared to clayey soil for similar Cd content. Clays are considered to bind the metals through particular adsorption sites (Rassaei et al. 2020).

## 5 Remediation of Cadmium-Contaminated Soils

As demographic pressure is increasing at a very rapid rate, it demands more land for the cultivation of crops to fulfill future dietary requirements. Therefore, remediation of Cd-polluted soils is the need of the hour. There are several approaches/strategies which are used to remediate Cd contaminated soils but the main objective of all these approaches is to save the environment as well as human health. Principally, there are three major approaches (physical, chemical, and biological) to decontaminate metal polluted soil (Fig. 5; Selvi et al. 2019). Several physicochemical approaches like soil excavation and disposal, soil washing, soil sodification and stabilization, and chemical extraction are practiced to remediate Cd-adulterated soils (Ahmad et al. 2012; Voglar and Lestan 2013). Although these approaches are beneficial in reducing metal contamination, these are not feasible owing to higher cost, ecological risks, and their adverse impacts on soil biota (Sorvari et al. 2007). Additionally, these approaches disturb the physical, chemical, and biological characteristics of the soil; hence making the soil unfit for cultivation (Marques et al. 2009). Along with physical and chemical methods, the biological approach is a promising and sustainable approach in which living organisms either microbes (microbial remediation) or plants (phytoremediation) are used to remediate the soil. As it is a natural, cheap to run, and environmentally sound strategy; therefore, it is widely accepted (Chibuike and Obiora 2014). Moreover, soil treatment with organic and inorganic amendments is found to be effective in declining the Cd absorption and accumulation in plants (Shan et al. 2016; Arshad et al. 2016). Therefore, this review describes the management of Cd contaminated soils by using different strategies to decrease Cd phytoavailability; thus, boosting crop growth and production. However, the adoption of the best possible strategy depends upon the time, cost, and availability as well as the future use of land.

### 5.1 Phytoremediation

Plantation for remediation of HMs is an eco-friendly, aesthetically acceptable, and cost-effective approach (Suman et al. 2018; Kurade et al. 2021). In this process, HMs can be degraded, removed, immobilized, or detoxified to mitigate their adverse impacts (Kamran et al. 2014). There are various strategies associated with bioremediation techniques such as phytoextraction, rhizofiltration, phytovolatilization, phytodegradation, rhizdegradation, phytostabilization, and phytorestoration (Yan et al. 2020). Phytoextraction is the

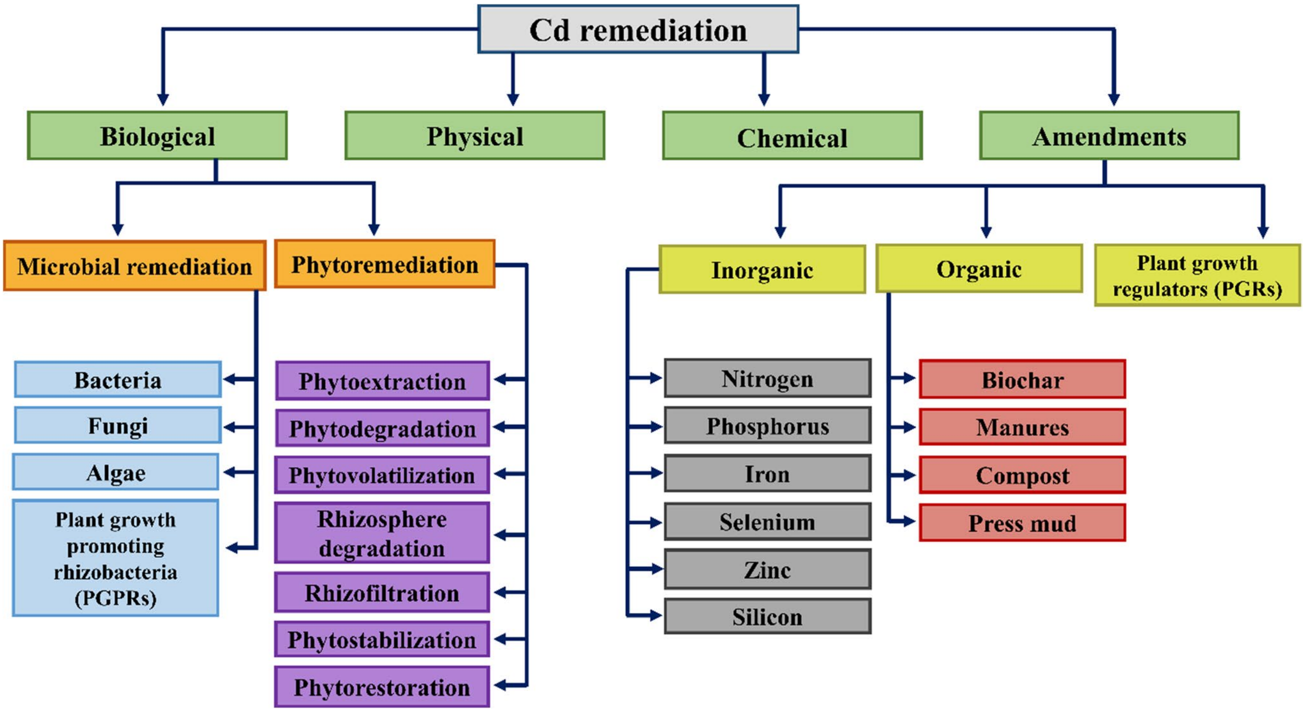

**Fig. 5** Possible management strategies to reduce cadmium toxicity

process of phytoremediation in which hyperaccumlator plants are used for the elimination of HMs from contaminated soils and water (Jacob et al. 2018). Hyperaccumulators are the plants having ability to grow on metalliferous soils and to accumulate high amounts of heavy metals in their aerial organs without suffering phytotoxic effects (Shrivastava et al. 2019). Hyperaccumulator plants are grown to absorb HMs in large amounts and accumulate them in above-ground biomass including shoots and leaves (Yan et al. 2020). Various Cd hyperaccumulator plants along with their accumulating efficacy are enlisted in Table 3. After phytoextraction, phytodegradation is the process that involves internal and external transformations. In internal phytotransformation, certain metabolic processes are involved; whereas in external phytotransformation, plant roots secrete various compounds that help in the breakdown of contaminants (Prasad and De Oliveira Freitas 2003). While in rhizofiltration, plants absorb and sequester the HMs from the soil into plant roots (Mahajan and Kaushal 2018). Phytostabilization is another process in phytoremediation that deals with the cultivation of plants to diminish HM mobility by metal valence reduction, sorption, complexation, or precipitation (US EPA 2000). Among phytoremediation approaches, phytoextraction is most common due to its higher efficacy and cost-effectiveness (Ali et al. 2013b). In conclusion, phytoremediation is a viable, socially, and economically acceptable, and eco-friendly approach to remediate Cd-polluted soils. Nonetheless, the concentration of Cd in edible portions of important food crops should be closely monitored to counteract the health risks posed by Cd.

### 5.2 Microbe-Assisted Remediation

Disintegration or transformation of HMs into innocuous form by using microbes is known as microbe-assisted remediation (Ojuederie and Babalola 2017). There are many forms of bioremediation such as use of bacteria (Kang et al. 2016), fungi (Zaidi et al. 2011), algae (Huq et al. 2007), actinomycetes (El-Sayed et al. 2011), plant growth-promoting rhizobacteria (Khan et al., 2009a, b) which are used to disintegrate, reduce and convert metallic elements into benign end products. Microbial bodies are highly successful in the remediation of Cd-contaminated soils due to their capability to precipitate and sequester (Table 4). Owing to the capability to grow and size in a controlled environment, and resilience to a vast range of ecological circumstances, bacteria has been proven an excellent biosorbent to remediate adulterated

**Table 3** Examples of Cd hyperaccumulators and their accumulation efficacy

| Plant species | Accumulation efficiency (mg kg$^{-1}$) | References |
|---|---|---|
| American black nightshade (*Solanum photeinocarpum*) | 158 | Zhang et al. (2011a) |
| Smooth mesquite (*Prosopis laevigata*) | 8176 | Buendía-González et al. (2010) |
| Yellowcress (*Rorippa globosa* Turcz.) | 219 | Sun et al. (2010) |
| Japanese honeysuckle (*Lonicera japonica*) | 286 | Liu et al. (2009) |
| Violettes (*Viola principis*) | 1200 | Wan et al. (2016) |
| Needle spikerush (*Eleocharis acicularis*) | 240 | Sakakibara et al. (2011) |
| Needle spikerush | 239 | Sakakibara et al. (2011) |
| Viola (*Viola Baoshanensis*) | 7076 | Li et al. (2010) |
| Saltbush (*Atriplex halimus*) | 606.5 | Nedjimi and Daoud (2009) |
| Alpine penny-cress (*Thlaspi caerulescens*) | 3000 | Sheoran et al. (2009) |
| Swinecress (*Coronopus didymus*) | 867.2 | Sidhu et al. (2017) |
| Water velvet (*Azolla pinnata*) | 740 | Rai, (2008) |
| Alpine penny-cress | 3000 | Sheoran et al. (2009) |
| Globe yellowcress (*Rorippa globose*) | > 100 | Wei et al. (2008) |
| Loosestrife (*Lysimachia deltoids*) | 212 | Wang et al. (2009) |
| Curly pondweed (*Potamogeton crispus*) | 49.09 | Sivaci et al. (2008) |
| Arabis (*Arabis paniculate*) | 434 | Tang et al. (2009) |
| Black nightshade | 387 | Sun et al. (2008) |
| Alpine penny-cress (*Thlaspi caerulescens*) | 5000 | Koptsik, (2014) |
| *Mallow* (*Malva sinensis* Cavan) | 154.30 | Zhang et al. (2010) |
| Holy Herb (*Siegesbeckia orientalis*) | 192.92 | Zhang et al. (2013b) |
| Yellowcress (*Nasturtium officinale* R.BR) | 133.52 | Lin et al. (2011) |
| Jewelweed (*Impatiens glandulifera*) | 1562 | Coakley et al. (2019) |

**Table 4** Microbial biosorption by different microbes

| Microbial group | Microbial biosorbent | pH | Temperature (°C) | Time (h) | Initial metal ion concentration (mg $L^{-1}$) | Sorption capacity (mg $g^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|
| Bacteria | *Kocuria rhizophila* | 8 | 35 | 1 | 150 | 9.07 | Haq et al. (2015) |
| | *Enterobacter cloacae* | 8 | 40 | 72 | 200 | 114.29 | Banerjee et al. (2015) |
| | *Beauveria bassiana* | 7.1 | 30 | 18 | 650 | 19 | Suksabye et al. (2015) |
| | *Pseudomonas aeruginosa* | 7.1 | 30 | 18 | 650 | 74 | Suksabye et al. (2015) |
| | *Bacillus subtilis* | 7.1 | 28–30 | 72 | 650 | 50 | Suksabye et al. (2015) |
| | *Streptomyces rimosus* | 8 | 50 | 24 | 100 | 63.3 | Selatnia et al. (2004) |
| Fungi | *Penicillium chrysogenum* | 5.5 | 30 | 73 | - | 210.2 | Deng and Ting, (2005) |
| | *Absidia cylindrospora* | 5.4 | 25 | 30 | - | - | Albert et al. (2018) |
| | *Glomus caledonium* | 7.8 | - | - | 7 | 14.7 | Wang et al. (2007) |
| Algae | *Asparagopsis armata* | 6 | - | 2 | 135 | 32.3 | Romera et al. (2007) |
| | *Codium vermilara* | 6 | - | 2 | 135 | 21.8 | Romera et al. (2007) |
| | *Cystoseira barbata* | 4 | 20 | 1 | 117.4 | 37.6 | Yalçın et al. (2012) |
| | *Pseudochlorococcum typicum* | 7 | 20 | 12 | 100 | 5.48 | Shanab et al. (2012) |
| | *Chlorella vulgaris* | 4.5 | 35 | 168 | 100 | 97.43 | Kumar et al. (2018) |

soil (Srivastava et al. 2015). According to Ziagova et al. (2007), *Staphylococcus xylosus* and *Pseudomonas* sp. effectively reduced the soil Cd content. Moreover, in an investigation, *Bacillus laterosporus* and *Bacillus licheniformis* were applied in Cd contaminated soil and found that Cd contents in soil were significantly reduced with sorption capacity of 159.5 mg $g^{-1}$ and 142.7 mg $g^{-1}$, correspondingly (Zouboulis et al. 2004). Fungal isolates are also effective in shrinking the Cd levels in the soil. Albert et al. (2018) examined the elimination of Cd using fungi *Absidia cylindrospora* from the soil and after three days, *A. cylindrospora* biosorbed about 50% of Cd present in the soil. Application of *Penicillium canescens* and *Penicillium chrysogenum* considerably reduced Cd toxicity (Say et al. 2003; Deng and Ting 2005). Soil treatment with fungal isolates *Rhizophagus irregularis* and *Funneliformis mosseae* improved the sunflower biomass and alleviated the Cd toxicity (Hassan et al. 2013). Fungi have different mechanisms of detoxification as compared to eukaryotes. Extracellular practices include metal chelation, precipitant formation as well as cell wall sorption; these processes significantly account for metal decontamination (Bellion et al. 2006). Likewise, algal isolates also have remediation potential against Cd. *Asparagopsis armata* and *Cystoseira barbata* substantially reduced the Cd concentration and were proved to effective in bioremediation of Cd (Romera et al. 2007; Yalçın et al. 2012). In conclusion, the application of appropriate microbial inoculum might be effective to amend Cd polluted soil effectively.

### 5.3 Remediation Through PGPRs

Plant growth-promoting rhizobacteria (PGPRs) were used to improve the growth and productivity of crops, now they are also used for remediation to overcome abiotic stresses (Nazli et al. 2020). Bacteria that are resilient to Cd stress even at higher concentration along with the capability to improve plant productivity are known to be Cd resilient PGPRs (Sharma and Archana 2016). PGPRs efficiently ameliorate the Cd phytotoxicity owing to their potential metabolic activity; as it involved direct and indirect mechanisms (Zhuang et al. 2007). Direct activities involve immobilization and biotransformation of Cd (Zaidi and Khan 2006); however, indirect activities involved improvement in the growth of metal stressed plants by yielding enzymes and metabolites including siderophores and ACC-deaminase (Burd et al. 2004). To defend the plants from Cd noxiousness, bacteria must possess Cd-resistant PGPR traits, capable of binding free $Cd^{2+}$ and active colonization in the rhizosphere (Pishchik et al. 2002). Moreover, Cd impervious as well as PGPR strains may influence metal-plant interactions in dual ways, i.e., by facilitating the uptake as well as aggregation of Cd in plant tissues; thus, enhancing the potential of hyperaccumulating plants (Table 5; Sharma and Archana 2016) or by diminishing the Cd uptake and translocation towards upper plant parts (particularly in non-hyperaccumulating plants) (Table 6; Kumar et al. 2011). It is well reported that the application of PGPRs through soil or seed inoculation not only improved the growth and biomass of plants but also proved helpful in Cd remediation in

**Table 5** Some examples of cadmium-resistant PGPR used for enhancing Cd accumulation in plants for phytoremediation/phytostabilization

| PGPR | Plant | Amount of PGPR | Method of application | Cd accumulation in plant (mg $kg^{-1}$) | | PGPR trait | References |
|---|---|---|---|---|---|---|---|
| | | | | Without bacteria | With bacteria | | |
| *Bacillus pumilus* E2S2 and Bacillus sp. E1S2 | Stonecrop (*Sedum plumbizincicola*) | $10^8$ cfu $mL^{-1}$ | Inoculation | 125 | 180 | Phosphate solubilization, IAA, ACC, and siderophores production | Ma et al. (2015) |
| *Bacillus megaterium* | Mustard | $10^8$ cfu $mL^{-1}$ | Seedling inoculation | 600 | 1500 | Phosphate solubilization | Jeong et al. (2012) |
| *Bacillus megaterium* | *Mustard* | $10^8$ cfu $mL^{-1}$ | Seedling inoculation | 800 | 1800 | Phosphate solubilization | Jeong et al. (2012) |
| *Enterobacter intermedius* | White mustard (*Sinapis alba*) | $10^8$ cfu $mL^{-1}$ | Soil inoculation | 17.4 | 28.4 | Indole-3-acetic acid production and P solubilization | Płociniczak et al. (2013) |
| Actinobacteria (Microbacterium sp. EX72) | Pussy willow (*Salix caprea*) | $10^9$ cfu $mL^{-1}$ | Seedling inoculation | 9 | 12.5 | Immobilization | Kuffner et al. (2010) |
| Pseudomonas sp. LK9 | Black nightshade | $10^8$ cfu $mL^{-1}$ | Soil inoculation | 230 | 292 | Organic acids and siderophores production | Chen et al. (2014c) |
| *Pseudomonas thivervalensis* | *Rapeseed* | $10^8$ cfu $mL^{-1}$ | Root inoculation | 609 | 647 | Immobilization | Chen et al. (2013) |
| Burkholderia sp. | *Rapeseed* | $10^8$ cfu mL – 1 | | 609 | 619 | | Chen et al. (2013) |
| *Cupriavidus taiwanensis* | Touch-me-not (*Mimosa pudica*) | $10^8$ cfu $mL^{-1}$ | Soil inoculation | 19.6 | 43 | Biodegradation, biosorption | Chen et al. (2008) |
| Pseudomonas sp. | Tomato | $10^8$ cfu $mL^{-1}$ | Soil inoculation | 274 | 309 | ACC deaminase activity, production of siderophores and Indole-3-acetic acid | He et al. (2009) |
| Bacillus sp. | Tomato | $10^8$ cfu $mL^{-1}$ | Soil inoculation | 274 | 293 | | He et al. (2009) |
| Rahnella sp. JN6 | *Rapeseed* | $10^8$ cfu $mL^{-1}$ | Inoculation | 90 | 140 | P solubilization, production of ACC deaminase and IAA | He et al. (2013) |
| Burkholderia sp. | Sedum alfredii | $10^8$ cfu $mL^{-1}$ | Seedling inoculation | 2428 | 2920 | IAA production, P solubilization | Guo et al. (2011) |
| Rahnella sp. | Black nightshade | $10^8$ cfu $mL^{-1}$ | Seedling inoculation | 55 µg $pot^{-1}$ | 110 µg $pot^{-1}$ | IAA, siderophores, ACC deaminase, phosphate solubilization | Yuan et al. (2013) |
| Rahnella sp. | Amaranthus *(Amaranthus Mangostanus)* | $10^8$ cfu $mL^{-1}$ | Seedling inoculation | 55 µg $pot^{-1}$ | 117 µg $pot^{-1}$ | IAA, siderophores, ACC deaminase, phosphate solubilizaiton | Yuan et al. (2013) |
| Rahnella sp. | Amaranthus (*Amaranthus hushypochondriacus*) | $10^8$ cfu $mL^{-1}$ | Seedling inoculation | 55 µg $pot^{-1}$ | 130 µg $pot^{-1}$ | IAA, siderophores, ACC deaminase, phosphate solubilizaiton | Yuan et al. (2013) |
| *Bacillus subtilis* | *Chinese violet cress* (*Orychophragmus violaceus*) | $5.2\times10^7$ cfu $mL^{-1}$ | Soil inoculation | 9.19 | 14.10 | Cd immobilization, improvement in plant growth, and root elongation | Liang et al. (2014) |

**Table 5** (continued)

| PGPR | Plant | Amount of PGPR | Method of application | Cd accumulation in plant (mg kg$^{-1}$) | | PGPR trait | References |
|---|---|---|---|---|---|---|---|
| | | | | Without bacteria | With bacteria | | |
| *Bacillus megaterium* | *Chinese violet cress* | $2.7 \times 10^7$ cfu mL$^{-1}$ | Soil inoculation | 9.19 | 25.86 | Cd immobilization, improvement in plant growth, and root elongation | Liang et al. (2014) |
| *Bacillus cereus* | *Chinese violet cress* | $3.2 \times 10^7$ cfu mL$^{-1}$ | Soil inoculation | 9.19 | 16.74 | Cd immobilization, improvement in plant growth, and root elongation | Liang et al. (2014) |
| *Pseudomonas aeruginosa* | *Chinese violet cress* | $3.4 \times 10^7$ cfu mL$^{-1}$ | Soil inoculation | 9.19 | 12.80 | Cd immobilization, improvement in plant growth, and root elongation | Liang et al. (2014) |
| Enterobacter sp. JYX7 and | *Polygonum pubescens* | $10^8$ cfu mL$^{-1}$ | Soil inoculation | 103 | 220 | IAA, siderophores, ACC deaminase, phosphate solubilizaiton | Jing et al. (2014) |
| Klebsiella sp. JYX10 | *Polygonum pubescens* | $10^8$ cfu mL$^{-1}$ | Soil inoculation | 103 | 211 | IAA, siderophores, ACC deaminase, phosphate solubilizaiton | Jing et al. (2014) |

*ACC* 1-aminocyclopropane-1-carboxylic acid; *IAA* indole acetic acid

**Table 6** Some examples of cadmium-resistant PGPR that reduce Cd accumulation in plants

| PGPR | Plant | Amount of PGPR | Method of application | Cd accumulation in plant (mg kg$^{-1}$) | | PGPR trait | References |
|---|---|---|---|---|---|---|---|
| | | | | Without bacteria | With bacteria | | |
| *Enterobacter aerogenes* | Black nightshade | $10^{8}$ cfu mL$^{-1}$ | Seedling inoculation | 550 | 467 | Cd immobilization and ACC deaminase activity, siderophore production | Kuffner et al. (2010) |
| Bradyrhizobium sp. | *Soybean* | $10^{8}$ cfu mL$^{-1}$ | Soil inoculation + Seedling inoculation (10 DAT) | 586 | 434 | Improved nutrient uptake | Guo and Chi (2014) |
| Chryseobacterium humi | Maize | $10^{8}$ cfu mL$^{-1}$ | Inoculation + surface spray | 21.5 | 4 | Reduced Cd translocation towards shoots and Cd immobilization | Moreira et al. (2014) |
| *Ralstonia eutropha* | Maize | $10^{8}$ cfu mL$^{-1}$ | Inoculation + surface spray | 21.5 | 6.5 | | Moreira et al. (2014) |
| Stenotrophomonas sp. | Wheat | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 132 | 118 | Improved stabilization | Ahmad et al. (2014) |
| Klebsiella sp | Wheat | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 132 | 95 | Improved stabilization | Ahmad et al. (2014) |
| Bacillus sp. | Wheat | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 132 | 103 | Improved stabilization | Ahmad et al. (2014) |
| Serratia sp | Wheat | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 132 | 130 | Improved stabilization | Ahmad et al. (2014) |
| *Pseudomonas putida* | Pak choi (*Brassica chinensis*) | $10^{7}$ cfu mL$^{-1}$ | Soil inoculation | 200 | 75 | Bio-adsorption | Xu et al. (2012) |
| *Pseudomonas putida* | Mung bean | | Soil inoculation | 3.3 | 0.7 | Cd bioaccumulation, P-type ATPases | Saluja and Sharma (2014) |
| Klebsiella sp | Maize | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 145 | 120 | Cd accumulation | Ahmad et al. (2014) |
| Serratia sp | Maize | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 145 | 140 | Cd accumulation | Ahmad et al. (2014) |
| Bacillus sp. | Maize | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 145 | 125 | Cd accumulation | Ahmad et al. (2014) |
| Stenotrophomonas sp. | Maize | $10^{9}$ cfu mL$^{-1}$ | Seed inoculation | 145 | 130 | Cd accumulation | Ahmad et al. (2014) |
| *Bacillus mycoides* | Maize | $10^{8}$ cfu mL$^{-1}$ | Seed inoculation | 987.22 | 668.17 | Phytoextraction and phytostsbilization | Malekzadeh et al. (2012) |
| *Micrococcus roseus* | Maize | $10^{8}$ cfu mL$^{-1}$ | Seed inoculation | 987.22 | 726.52 | Phytoextraction and phytostsbilization | Malekzadeh et al. (2012) |

*ACC* 1-aminocyclopropane-1-carboxylic acid

Cd-contaminated soils. Jing et al. (2014) collected two Cd-resistant PGPRs strains namely Klebsiella sp. JYX10 and Enterobacter sp. JYX7 from *Polygonum pubescens* to inoculate rapeseed plants for Cd aggregation. It was observed that both the bacterial strains efficiently accumulated Cd and improved plant growth by production of IAA, siderophore, ACC deaminase and/or by increasing the bioavailability of Cd in soil. Dell'Amico et al. (2008) also probed the remediation potential of Mycobacterium sp. ACC14, *Pseudomonas Fluorescens* ACC9, and *P. tolaasii* ACC23 in rapeseed and noticed enhanced uptake of Cd. ACCD activity was responsible for better root growth in the initial stages of plant growth, siderophore and IAA production might facilitate the mobilization of nutrients, hormonal balance, and, thus, plant growth. Likewise, Burkholderia sp. improved the growth and biomass of *Sedum alfredii* in Cd polluted soil and remarkably removed the Cd from the soil and improved the phytoextraction efficacy. Burkholderia sp. D54 produced IAA and siderophores, synthesize ACC deaminase, and solubilize inorganic phosphate and metal bearing minerals, which together may account for significantly increased growth of S. alfredii (Guo et al. 2011). Liang et al. (2014) investigated the capability of *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Bacillus megaterium*, and *Bacillus cereus* inoculation in improving the growth and enhancing the Cd accumulation in *Orychophragmus violaceus* in Cd contaminated soil. The outcomes highlighted that application of bacterial strains stimulated the root elongation, enhanced the Cd mobility, and improved the Cd accumulation in *O. violaceus*. Moreover, *Bacillus megaterium, Bacillus cereus*, and *Bacillus subtilis*, *Pseudomonas aeruginosa* accumulated 181.4%, 82.15%, 53.43%, and 39.28% Cd from the soil, respectively.

### 5.4 Chemical Remediation

Along with phytoremediation, soil remediation can be escalated via chelation strategy in which different chelating agents are applied in the growth medium which forms several coordinate bonds by single metal ions (Habiba et al. 2015; Feng et al. 2020). There are several types of chelating agents such as EDTA ethylenediaminetetraacetate, EGTA ethylenebis(oxyethylenenitrilo)tetraacetic acid, DTPA diethylenetriaminepentaacetic acid, CDTA trans-1,2-diaminocyclohexane-N, N, N0, N0 -tetraacetic acid diethylenetriaminepentaacetic acid, IDSA iminodisuccinic acid, and EDDS (S,S-ethylenediamine disuccinic acid), used to enhance mobilization as well as intake of HMs by resistant plants (Shaheen and Rinklebe 2015; Zaheer et al. 2015). Chelating agents promote the absorption and subsequent translocation and amassing of HMs in plant parts. This is due to escalated desorption of HMs from the matrix to solution in soil, change in the form of HM in soil, enhance the content of available HM in soil, and facilitate translocation towards xylem tissues and improve metal transport towards aerial structures (Bian et al. 2018). Predominantly, EDTA is the most widely used chelating agent owing to its strong affinity and slower biodegradability (Saifullah et al. 2009). The higher binding affinity of EDTA for HMs enables the release of HMs from insoluble to soluble phase (Nowack 2002). The application of another chelator DTPA is also proved useful in Cd complexation. It is well reported that the application of DTPA enhances the solubility of Cd and improves its uptake in plants (Mehmood et al. 2013). Wang et al. (2020) explored the potential of EDDS application at 1 mM and 3 mM in *Tagetes patula* L. and *Phytolacca americana* L. and results revealed significant accumulation of biomass in both tested plants. Likewise, sundance stain of sunflower hyperaccumulated Cd with 0.3 g $kg^{-1}$ EDTA (Munn et al. 2008), additionally, it was noticed that response of EDTA in remediation varied with EDTA concentration. Application of EDTA at 0.1 g $kg^{-1}$ in black nightshade had a positive effect on Cd uptake and availability and enhanced the phytoremediation efficiency (Sun et al. 2008). Similarly, the application of IDSA, EDTA, and EDDS in hydroponically grown maize substantially enhanced the Cd uptake in maize biomass (Zhao et al. 2010). Hence, chelating agents help to remediate the Cd polluted soils. The application of these chelators substantially improved the Cd uptake in above-ground biomass of many important plants (Table 7). These studies suggest that the application of chelating agents is an effective strategy for Cd remediation from the soil.

### 5.5 Plant Growth Regulators-Assisted Remediation

Modulation of plant growth regulators (PGRs) profile is another tolerance strategy of plants regarding Cd stress (Asgher et al. 2015; Hasan et al. 2019). Amongst main PGRs, phytohormones including auxins, cytokinins (CKs), gibberellins (GA), abscisic acid (ABA), jasmonic acid (JA), brassinosteroids (BRs), ethylene, nitric oxide (NO), and polyamines are accounted to play a significant role concerning developmental processes of plants. Plant growth regulators substantially account for enhancing plant adaptability to survive in Cd polluted growing medium (Table 8; Piotrowska-Niczyporuk et al. 2012). Furthermore, PGRs (auxin, GA, and CKs) are also involved in phytoextraction (Bulak et al. 2014). For coping with Cd stress, various plants have developed an endogenous defense mechanism with the production of phytohormones. However, under higher Cd stress, the efficacy of the internal defense system was reduced. Thus, the exogenous application of phytohormones might improve plant tolerance under Cd stress. Application of 50 mM salicylic acid (SA) as pre-treatment reduced Cd accumulation in wheat, resulting in declined MDA content (Shakirova et al. 2016). Pre-treatment with SA at the rate of 500 mM for 20 h improved the plant water relations, photosynthetic pigments, C-fixation, and ABA concentration; whereas reduced the $H_2O_2$, MDA, and proline content in Cd exposed seedlings of wheat (Moussa and El-Gamal 2010a, b). Similarly, improved Cd tolerance was observed in brassica upon the application of SA which resulted in mitigating the Cd-elicited oxidative damages (Ahmad et al. 2011). Additionally, SA treatment reduced the Cd contents in biomass of Chinese cabbage as well as rapeseed (Mba et al. 2007; Ahmad et al. 2011; Ali et al. 2015). In tomato, the pretreatment of SA abridged the Cd-induced oxidative stress by dint of reduced formation of

**Table 7** Effect of chelates application for remediation of Cd in soil

| Plant species | Chelate applied | Dose applied | Concentration in biomass (mg kg$^{-1}$) | | Soil metal (mg kg$^{-1}$) | References |
|---|---|---|---|---|---|---|
| | | | Before | After | | |
| Potherb mustard | EDTA | 5 mM | 4.26 | 5.75 | 4.87 | Guo et al. (2019) |
| Potherb mustard | EDTA | 10 mM | 4.26 | 5.40 | 4.87 | Guo et al. (2019) |
| Four o'clock (*Mirabilis jalapa* L.) | EDTA | 1 mM | 61.09 | 111.74 | 25 | Wang and Liu, (2013) |
| Four o'clock | EGTA | 1 mM | 61.09 | 92.27 | 25 | Wang and Liu, (2013) |
| *Marigold* (*Calendula officinalis* L.) | EDTA | | 921 | 1200 | 100 | Liu et al. (2010) |
| Impatiens (*Impatiens walleriana*) | EDTA | 0.1 mmol | 410 | 538 | 20 | Wei et al. (2012) |
| French marigold (*Tagetes patula*) | EDTA | 0.1 mmol | 325 | 496 | 20 | Wei et al. (2012) |
| Maize | IDSA | 500 µmol L$^{-1}$ | 2.5 | 44 | 20 | Zhao et al. (2010) |
| Maize | EDTA | 500 µmol L$^{-1}$ | 2.5 | 15 | 20 | Zhao et al. (2010) |
| Maize | EDDS | 500 µmol L$^{-1}$ | 2.5 | 13 | 20 | Zhao et al. (2010) |
| Black nightshade | EDTA | 0.1 g kg$^{-1}$ | 143.5 | 183.8 | 25 | Sun et al. (2008) |
| mustard | EDTA | 1050 kg ha$^{-1}$ | 0.36 | 0.44 | 0.23 | Bloem et al. (2017) |
| Spinach | EDTA | 1.25 mM | 0.04 | 0.14 | 6.8 | Suthar et al. (2013) |
| Spinach | EDTA | 2.5 mM | 0.04 | 0.18 | 6.8 | Suthar et al. (2013) |
| Spinach | EDTA | 5 mM | 0.04 | 0.22 | 6.8 | Suthar et al. (2013) |
| Indian mustard | EDTA | 0.5 mM | 310 | 420 | 30.7 | Ramamurthy and Memarian 2013) |
| Indian mustard | EDTA | 1 mM | 310 | 500 | 30.7 | Ramamurthy and Memarian (2013) |
| Indian mustard | EDTA | 2 mM | 310 | 640 | 30.7 | Ramamurthy and Memarian (2013) |
| mustard | EDTA | | 0.25 | 1.24 | 3 | Dede et al. (2012) |
| Sunflower | EDDS | 5 mmol kg$^{-1}$ | 1.7 mg pot$^{-1}$ | 1.6 mg pot$^{-1}$ | 50 mg kg$^{-1}$ | Moslehi et al. (2019) |
| French marigold | EDDS | 3 mM | 428.64 | 528.49 | | Wang et al. (2020) |
| French marigold | EDDS | 1 mM | 428.64 | 518.26 | | Wang et al. (2020) |
| Pokeweed (*Phytolacca americana* L.) | EDDS | 3 mM | 8.21 | 32.82 | | Wang et al. (2020) |
| Pokeweed | EDDS | 1 mM | 8.21 | 42.58 | | Wang et al. (2020) |

*EDTA* ethylene diamine tetra acetate; *EGTA* ethylene glycol tetraacetic acid; *IDSA* imino di succinic acid; *EDDS* (S,S-ethylene diamine disuccinic acid)

proline, MDA, and $H_2O_2$ contents (Koç et al. 2013). Furthermore, ascorbic acid treatment has also been reflected to be an effective measure in mitigating the Cd deterrent impacts in rice regarding oxidative damages (Chao et al. 2010). Likewise, exogenously applied JA improved the APX action in Cd exposed rice plants with reference to control (Singh and Shah 2014a). Besides, the application of methyl jasmonate improved the response of antioxidants (CAT, SOD, POD, and GR) under Cd-stressed rice seedlings (Singh and Shah 2014b). Application of DA-6 (diethyl aminoethyl hexanoate) augmented the Cd extraction efficiency and enhanced the biomass accumulation in *Amaranthus hybridus* Linn. (Li et al. 2018) and ryegrass (He et al. 2019). Exogenous supply of 5-aminolevulinic acid (ALA) improved plant resistance to Cd tolerance (Ahmad et al. 2017), by improving the antioxidant enzyme actions in rapeseed under Cd-stressed soil (Ali et al. 2013a, 2013b). Similarly, the treatment of NO in the form of sodium nitroprusside reduced the Cd prompted oxidative damages in wheat seedlings (Singh et al. 2008) and rice seedlings (Xu et al. 2015). Foliar supply of gibberellic acid (10 µM) significantly improved the leaf area, dry biomass, and photosynthetic activity in mustard and reduced oxidative stress and ethylene production (Masood et al. 2016). Brassinosteroid (BR) application in mustard improved photosynthesis, proline contents, and antioxidant activities (Hayat et al. 2007). Priming of wheat seeds with polyamines, spermine, and spermidine enhanced the seedling growth, starch, ascorbic acid, and protein concentration

**Table 8** Effect of plant growth regulators (PGR) on cadmium (Cd) uptake by different plants

| Plant growth regulator | Dose | Plant | Experiment type | Cd treatment | Duration (days) | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Auxin | 0, 100, 200, 300, 400 µM | *Arbaidopsis thaliana* | Pot | 10 µM $CdSO_4$ | 14 | Improved rooting and root growth under Cd stress | Vitti et al. (2013) |
| Brassinosteroids | 0.1 µM | Tomato | Greenhouse | 100 µM $CdCl_2 \cdot 2.5H_2O$ | 40 | BR application alleviated the negative impacts of Cd on growth and photosynthesis by improving antioxidant enzyme activity, xenobiotic detoxification capacity, and secondary metabolism | Ahammed et al. (2013) |
| Salicylic acid | 500 µM | Hemp (*Cannabis sativa* L.) | Pot | 0, 25, 50, and 100 mg $kg^{-1}$ $CdCl_2.2.5H_2O$ | 40 | SA pretreatment reduces Cd toxicity in seedlings resulting from decreased Cd uptake, improved photosynthesis, and increased SOD and POD activity | Shi et al. (2009) |
| Gibberellic acid | $10^{-9}$, $10^{-7}$, and $10^{-5}$ M | Congress weed (*Parthenium hysterophorus*) | Pot | 17.06 g $(CH_3COO)_2Cd \cdot 2H_2O$ | 60 | The $GA_3$ treatments accumulated more than 50% of the total Cd in the roots | Hadi et al. (2014) |
| Polyamines | 1 mM | *Gracilaria dura* | Laboratory | 0.4 mM $CdCl_2$ |  | PA regulates the stabilization of DNA methylation by decreasing the events of cytosine demethylation in a mechanism to alleviate the Cd stress | Kumar et al. (2012) |
| salicylic acid | 0, 60, 120, 240 and 500 mM | Soybean | Hydroponic | 50 µM $CdCl_2$ | 5 | Increased content of chlorophyll, GSH, CAT, and SOD activities and reduction of Cd content in soybean leaves | Noriega et al. (2012a) |

**Table 8** (continued)

| Plant growth regulator | Dose | Plant | Experiment type | Cd treatment | Duration (days) | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Jasmonic acid | 2, 20, 100, and200 µM | Soybean | Hydroponic | 50 µM Cd | 5 | JA treatment may be involved in inhibition of lipid peroxide formation through the stimulation of nonenzymatic antioxidant machinery as well as the increase of an antioxidant enzyme | Noriega et al. (2012b) |
| Ethylene | 200 µL $L^{-1}$ | Mustard | Pot | 50 µM $CdCl_2$ | 30 | Application of ethephon alleviated Cd-induced oxidative stress noticeably mustard cultivar | Asgher et al. (2014) |
| Ethylene | 200 µL $L^{-1}$ | Mustard | Pot | 200 mg $kg^{-1}$ $CdCl_2$ | 30 | Ethylene application induced the Cd tolerance and photosynthetic inhibition was alleviated | Masood et al. (2012) |
| Salicylic acid | 50 µM | Mung bean (*Phaseolus aureus*) & common vetch (*Vicia sativa*) | Pot | 0, 50, and 100 µM $CdCl_2$ | 6 | SA application induced Cd tolerances associated with increases in apoplastic and symplastic antioxidant enzyme activities | Zhang et al. (2011b) |
| Salicylic acid | 1.5 mM | Tomato | Hydroponic pot | 0, 10, 25, and 50 µM | 25 | The salicylic acid application under Cd stress increased leaf length and fresh weight. Reduction in MDA and proline content and decrease in soluble protein and chlorophyll content compared with control | Çanakci and Dursun (2012) |
| Salicylic acid | 0.75 mM | Cucumber | Hydroponic pot | 0, 25, 50, and 100 µM $CdCl_2$ | 15 | Seedling length, leaf length, and chlorophyll contents improved even at 50 µM Cd stress. There were no positive results of SA application at above 50 µM stress | Çanakci and Karaboğa (2013) |

**Table 8** (continued)

| Plant growth regulator | Dose | Plant | Experiment type | Cd treatment | Duration (days) | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Salicylic acid | 0.5 mM | Tomato | Hydroponic pot | 0, 20, 40, and 100 µM $CdCl_2$ | 5 | Nitrate reductase activity was increased on the first day and then decreased on the third and fifth day of treatment. The fifth day increased MDA and $H_2O_2$ in SA, Cd treatments | Koç et al. (2013) |
| Nitric oxide | 500 and 1000 µM | Pea | Hydroponic pot | 0 and 25 µM $CdCl_2$ | 15 | Improved leaf size and thickness of lamina, reduced intercellular spaces in mesophyll under Cd stress | Tran et al. (2013) |
| Abscisic acid | 10 µM | Mungbean | Hydroponic | 1, 3, 5, 7 and 9 µM $CdCl_2$ | 3 | Fresh weight and number of adventitious roots improved with ABA treatments and reduced the SOD, APX, POD, CAT, GSH, and ASA in roots under Cd stress | Li et al. (2014b) |
| Nitric oxide | 500 and 1000 µM | Lettuce | Hydroponic | 0 and 100 µM | 30 | Improvement in plant growth, biomass, photosynthesis, and activities of antioxidant enzymes and decreased Cd uptake under Cd stress | Xu et al. (2014) |
| Nitric oxide | 8.94 mg | Lettuce | Pot | 0 and 50 mg $kg^{-1}$ | 20 | Increase in chlorophyll content, antioxidant enzyme activities, and the uptake of micronutrients, while a decrease in Cd-induced oxidative damages was noticed in SNP + Cd treatments | Xu et al. (2015) |

**Table 8** (continued)

| Plant growth regulator | Dose | Plant | Experiment type | Cd treatment | Duration (days) | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Jasmonic acid | 0.01 mM | Faba bean (*Vicia faba*) | Pot | 150 mg $L^{-1}$ $CdSO_4.8H_2O$; | 35 | JA mitigates the negative effects of Cd stress in faba bean plants by inhibiting the accumulation of Cd, $H_2O_2$, and MDA, and by augmenting osmolyte and antioxidant activities that decrease oxidative stress | Ahmad et al. (2017) |
| Salicylic acid | $10^{-4}$ M | Peppermint (*Mentha piperita* L.) | Pot | 30, 60 and 120 mg $kg^{-1}$ $CdCl_2$ | | SA application substantially reduced Cd toxicity, enhanced photosynthesis by increasing the activity of RuBisCo and carbonic anhydrase and reduces oxidative stress by reducing the production of free radicals by reducing free radical production and reducing GSH pool | Ahmad et al. (2018) |
| Salicylic acid | 10 µM | Rice | Hydroponic pot | 150 µM $CdCl_2$ | 14 | Application of Sa as rooting medium alleviated Cd-induced inhibition of the photosynthetic apparatus in rice seedlings | Yotsova et al. (2018) |
| Salicylic acid | 50 µM | Duckweed (*Lemna minor*) | Laboratory | 10 µM $CdCl_2$ | 7 | SA considerably reduced the adverse effects of Cd on the SOD, POD, CAT, APX, and GR in the fronds of L. minor | Lu et al. (2018) |

**Table 8** (continued)

| Plant growth regulator | Dose | Plant | Experiment type | Cd treatment | Duration (days) | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Salicylic acid | 20 µM $CdCl_2$ | Pygmy waterlily (*Nymphaea tetragona* Georgi) | Hydroponic Pot | 150 mg $L^{-1}$ $CdCl_2$ | 9 | Pretreatment of SA lowered the MDA and proline concentrations but enhanced the contents of photosynthetic pigments, glutathione, non-protein thiol, and phytochelatins | Gu et al. (2018) |
| Salicylic acid | 600 µM | Potato | Pot | 200 µM $CdCl_2$ | 28 | foliar-applied SA excellently alleviated the negative effects of Cd on potato plants, as demonstrated by enhanced endogenous SA content, leaf tissue RWC, proline content, and antioxidase activities, reduced accumulation of tissue MDA, $H_2O_2$ and $O_2^-$, and induction of SA and ROS metabolism-related genes in plants exposed to Cd stress | Li et al. (2019) |
| Indole acetic acid | 500 mg $L^{-1}$ | Mustard | Pot | 15 mg $kg^{-1}$ $CdCl_2$ | | IAA inhibited the negative effects of Cd. Meanwhile, IAA decreased MDA and $H_2O_2$ content of mustard and increased activities of antioxidant enzymes | Chen et al. (2020) |

*SOD* superoxide dismutase; *POD* peroxidase; *GSH* reduced glutathione; *CAT* catalase; *MDA* malondialdehyde; *APX* ascorbate peroxidase; *AsA* ascorbic acid; *GR* glutathione reductase; *IAA* indole acetic acid and reduced the MDA, $H_2O_2$, and proline contents under Cd-stressed conditions (Rady and Hemida 2015). Proline is an important metabolite for plant adaptation, protection, and tolerance to Cd stress. Accumulation of proline in plants is recognized as a strategy to counteract Cd stress by adjusting osmotic potential, stabilization of membrane structures (Amari et al. 2017; Semida et al. 2018), and reduction of oxidative stress (Rady et al. 2019). Foliar spray of proline and glycinebetaine caused a significant improvement in growth and physiochemical attributes of two wheat cultivars under Cd stress. Proline and glycinebetaine had markedly enhanced shoot and root fresh weight, leaf phenolics, lesser degradation of chlorophylls, and accumulation of MDA and $H_2O_2$ contents under Cd stress (Rasheed et al. 2014). Similarly, Cd-stressed olive plants treated with proline showed an increase of antioxidant enzymes activities, photosynthetic activity, nutritional status, plant growth and oil content of olive fruit (Zouari et al. 2016). So, the use of the aforementioned PGRs can be an effective strategy to boost the growth and development of plants grown in a Cd-stressed environment.

## 5.6 Use of Inorganic Amendments for Remediation

Fertilization of different mineral amendments might be an effective option in decreasing the Cd uptake and accumulation in plants. Some individual mineral elements have been highlighted here which considerably decrease the Cd accumulation in plants.

### 5.6.1 Nitrogen

Nitrogen is an important macronutrient for plants with an imperative function in plant productivity and grain nutrition (Hirel and Krapp 2020). Various findings have reported that N application in soil significantly influences the Cd dynamics (Li et al. 2013; Ishikawa et al. 2015). Lin et al. (2011) reported escalated Cd uptake in rice plants under N deficient conditions; subsequently, abridged the plant growth, which reflects that adequate N application might decline Cd deterrent impacts. However, the intensity of Cd phytotoxicity may vary with different N speciation. For instance, Yang et al. (2016a) observed that excessive quantity of $NO^{3-}$ in nutrient solution enhanced the Cd content in rice biomass and grains contrary to control. In another study, the highest N and lowest Cd concentration were observed in paddy biomass with the application of $(NH_4)_2SO_4$ compared with $Ca(NO_3)_2$ and $NH_4NO_3$ under hydroponic conditions (Hassan et al. 2005). Similarly, Gao et al. (2010) probed the role of source and time as well as the method of application of nitrogenous fertilizers regarding Cd toxicity in wheat plants under conventional as well as conservation tillage systems. The outcomes reflected that N-supply as band placement resulted in enhanced Cd content in plants contrary to dual-banded placement which signifies that higher N accessibility diminishes the Cd uptake. Ammonia enrichment enhanced grain Cd concentration in comparison to ammonium nitrate and urea. Increasing the N rate from 60 to 160 and 240 kg $ha^{-1}$, reduced the Cd absorption in potato, regardless of potato cultivars (Jonsson and Asp 2011). Thus, the selection of proper N source, rate, and method of the application might be a feasible preference to grow plants in Cd-polluted soils with minimum risk of Cd entry into the food chain.

### 5.6.2 Phosphorus

Reduction in Cd toxicity by using phosphorus (P)-containing amendments is well known in several crops (Rizwan et al. 2016a, b). Phosphorous enrichment as $CaH_4P_2O_8$ under various levels of $CdSO_4$ improved the spinach biomass and reduced the Cd concentration owing to reduced exchangeable as well as carbonic formations of Cd in relation to control (Dalir et al. 2012). The supply of P as mono-ammonium phosphate (MAP) reduced the Cd content in wheat grains and improved the gas exchange parameters and plant growth (Arshad et al. 2016). Rochayati et al. (2011) assessed the impact of P on Cd uptake in maize, and it was observed that the application of reactive P rock enhanced the Cd absorption by maize plants. Conversely, Jiang et al. (2007) observed that $H_2PO_4$ application in solution culture significantly reduced the Cd uptake by maize. This indicated that P fertilizer type and growing medium substantially affect the Cd behavior regarding plant uptake. Shi et al. (2015) reported that Cd concentrations in wheat grains were correlated with the concentration of P in straw and grains of wheat. Whereas, Jafarnejadi et al. (2011) documented that the overdose of phosphatic fertilizers augmented the Cd content in the top layer of soil and wheat grains. This indicated that P fertilization should be cautiously used in Cd-polluted soils to diminish Cd entrance in the food chain via crops.

### 5.6.3 Zinc

Zinc is an important micronutrient for plants; however, owing to physico-chemical similarities with Cd, competition exists at the soil matrix for adsorption as well as at root surfaces for uptake. It has been stated by numerous studies that enrichment of Zn in soil reduced the Cd concentration in plants (Singh and Shivay 2013; Adil et al. 2020). Kukier and Chaney (2002) observed that Zn application diminished Cd content in shoots; while, in case of rice grains, its concentration showed variation in response to contamination level as well as the composition of nutrient solution. Similarly, Liu et al. (2007) probed that Cd toxicity was reduced in durum wheat seedlings after the Zn application. The concentration of Cd in Chinese cabbage reflected a contrary response to Zn enrichment. Accordingly, it was proposed that Zn application on foliage might be helpful in reducing the Cd concentration in Chinese cabbage (Tang et al. 2016). Translocation of Cd in wheat shoots was significantly reduced by enhancing the Zn interactions in soil solution fraction (Green et al. 2003). According to Koleli et al. (2004) the positive response of Zn regarding Cd toxicity alleviation might be the outcome of the competition for particular metalloenzymes, critical cellular organelles and improved defense mechanism in Cd exposed plants. Cakmak et al. (2000) suggested that reduction in Cd concentration in wheat grains is also ascribed to Zn associated competitive retardation of Cd transmission into the phloem. Moreover, the corresponding treatment of Zn to wheat flag leaf along with Cd impeded the transport of Cd towards grains (Harris and Taylor 2001).

#### 5.6.4 Iron

The application of iron (Fe) could be a potential amendment in deterring the Cd accumulation in plants. It is well documented that Fe nutrition could alleviate Cd content under both field and laboratory conditions (Zhou et al. 2015). Tomato seedlings were planted in a hydroponic growing medium with diverse levels of Fe, along with treatment having no Fe supply, there was substantially higher Cd uptake by tomato seedlings compared with other treatments. So, it was suggested that deficiency of Fe induced variations in root exudation, leading towards augmented Cd availability (Bao et al. 2010). Similar outcomes have also been highlighted in diverse studies (Zhou et al. 2015). Iron enrichment in rice grown on Cd-contaminated soil considerably resulted in the restoration of photosynthetic $e^-$ transmission system compared with controlled conditions (Sebastian and Prasad 2015b). The efficacy of Cd uptake differs with different forms of Fe. For example, Fe and Cd uptake were considerably higher with the application of Fe (III) citrate instead of Fe (III) EDTA in similar amounts (Csog et al. 2011). The studies revealed that Fe supply can be an effective option to reduce Cd phytotoxicity but its various sources must be assessed before its application.

#### 5.6.5 Selenium

A naturally occurring metalloid that possesses the potential for better plant productivity at minimal dose but elicits its adverse impacts at a higher dose (Mostofa et al. 2017). Various studies highlighted that selenium (Se) application can reduce the Cd uptake as well as the deterrent impacts on crops (Hawrylak-Nowak et al. 2014; Sun et al. 2016; Xie et al. 2021). Selenium supply inhibited Cd uptake by paddy seedlings and improved the nutrient status under Cd stress (Feng et al. 2013). The selenium-mediated decrease in Cd content in rice biomass might be owing to a reduction of Cd solubility in soil (Hu et al. 2014). Moreover, it was observed that nutrient status was improved with a reduction in lipid peroxidation and Cd concentration when the wheat seedlings were exposed to Se (Zembala et al. 2010). Under Cd-stressed environment, promising results with Se supply in improving the plant biomass and hampering root Cd absorption has been documented in broccoli (Pedrero et al. 2008), pepper (Mozafariyan et al. 2014), garlic (Sun et al. 2010a, b), cucumber (Sun et al. 2016), and tomato (Abdullah et al. 2016). These findings showed that Se fertilization reduced Cd concentrations with significant improvement in plant growth, C-fixation, and nutritional status. Moreover, the effect of Se on Cd in different plants is Se as well as Cd dose-dependent (Ding et al. 2014). In general, Se is significantly found to elicit a protective impact on Cd exposed plants.

#### 5.6.6 Silicon

Silicon (Si) is the second most abundant element on earth's crust and widely reported for the alleviation of abiotic stress in plants (Rizwan et al. 2015, 2016a; Keller et al. 2015). Quite a few studies revealed that Si application declined Cd toxicity in wheat (Rizwan et al. 2012, 2016c; Thind et al. 2020), rice (Nwugo and Huerta 2010; Kim et al. 2014), maize (Mihalicova et al. 2014; Vaculik et al. 2015), cotton (Farooq et al. 2016), Chinese cabbage (Wu et al. 2016a, b), cucumber (Feng et al. 2010) and tomato (Wu et al. 2015). da Cunha et al. (2008) probed that Si application at the rate of 200 ppm under 10 ppm Cd enhanced the root and shoot biomass of maize considerably. da Cunha and do Nascimento (2009) suggested the Si aggregation in root endodermis, as well as pericycle, seems to play a vital role in increasing the tolerance of Cd toxicity in maize. In another study, the application of Si enhanced the Cd deposition in shoot and roots cell walls and augmented suberin lamellae deposition and improved CAT, POD, and SOD activities in maize seedlings (Lukacova et al. 2013). Cadmium concentration significantly reduced in grains of durum wheat with Si supply compared with untreated treatments (Naeem et al. 2015). The Si-mediated reduction of Cd concentration in wheat might be owing to a rise in soil pH (Rizwan et al. 2012) and/or reduction in the concentration of extractable Cd in soil and by enhancing Cd accumulation in roots (Naeem et al. 2015). Similarly, Si application improved rice growth by reducing the Cd uptake and ameliorating the structure and function of roots as compared to control (Kim et al. 2014). Nwugo and Huerta (2008) reported that Si application in the Cd-contaminated field enhanced the photosynthetic efficiency of Cd-stressed rice. Moreover, it maintained the structure and integrity of rice leaves and roots under Cd-stressed conditions (Tripathi et al. 2012). However, a lower concentration of Si in soil did not change the soil pH and enhanced the Cd concentration in shoots and bulbs of garlic compared with control (Wang et al. 2016c). Thus, the application of Si can be a useful option to improve the growth of plants under the Cd-stressed environment.

## 5.7 Use of Organic Amendments for Remediation

Generally, organic supplements are used in metal-polluted soils in various ways to reduce Cd uptake in plants (Juang et al. 2012; Lwin et al. 2018). Numerous studies have reported the use of organic amendments in Cd contaminated soils and their effects in reducing its uptake in plants (Tables 9, 10).

### 5.7.1 Biochar

Biochar is a stable source of organic carbon is produced with the heating of biomass at a higher temperature (300–1000 °C) in the absence of $O_2$ (Verheijen et al. 2010). The fame of biochar as a soil amendment has significantly increased in recent years due to its fundamental advantages including soil conditioning, improvement in soil pH, fertility, water holding capacity, carbon sequestration, recycling of nutrients, and remediation of soil contaminants (Zhang et al. 2013c; Ali et al. 2017, Ur Rehman et al. 2020). Biochar acts as an adsorbent to sequester HMs in soil (Hussain et al. 2017). It is well reported in the published literature that the application of biochar in pot and field experiments significantly improved the growth, biomass, and economic yield in Cd-contaminated soils (Table 9).

Zheng et al. (2012) stated that the use of rice straw biochar significantly reduced Cd concentration in rice compared with rice husk and bran. Similarly, biochar derived from rice straw reduced the Cd concentration in rice and reduced MDA, proline, as well as CAT, POD, and SOD activities under Cd stressed conditions (Zhang et al. 2014a). Biochar application reduced toxic metal concentrations including Cd in wheat (Ok et al. 2015), rice (Bian et al. 2016), sunflower (Sneath et al. 2013), mustard (Choppala et al. 2015), jack bean (Puga et al. 2015), garlic (Song et al. 2014), lettuce (Kim et al. 2015a, b) pepper (Xu et al. 2016), soybean (Waqas et al. 2014) and mung bean (Prapagdee et al. 2014). However, the biochar effects towards metal immobilization and uptake by crop plants differed with pyrolysis temperature, biochar, and soil type (Khan et al. 2015b; Rizwan et al. 2016c; Woldetsadik et al. 2016). In crux, biochar application is an eco-friendly approach to grow crops successfully in Cd-contaminated soils with reduced Cd contents in their above-ground parts.

### 5.7.2 Compost

Compost is a well-decomposed organic material produced from animals and plants under anaerobic conditions (Stanislawska-Glubiak et al. 2015). It improves the soil structure and fertility status; as it comprises organic matter contents. Moreover, the application of compost is also helpful in improving crop productivity in Cd-contaminated soils. For instance, the application of compost increased the growth and biomass of corn under Cd-stressed conditions and it also improved the tolerance index (Ahmad et al. 2015). Sato et al. (2010) experimented to evaluate the efficacy of compost derived from swine, cattle, and poultry on uptake and availability of Cd by spinach. After four years of study, it was concluded that the application of amendments reduced Cd concentration in spinach. Moreover, the repeated application enhanced the P concentration in soil. The authors also suggested that compost derived from cattle might be a more effective amendment to reduce Cd uptake by spinach compared with other treatments. Likewise, compost application reduced bioavailable Cd in soil and uptake by rice plants (Juang et al. 2012). It has been reported that the efficiency of composted manure in reducing the toxic metal concentration is significantly higher as compared to fresh manure (Irshad et al. 2014).

### 5.7.3 Manures

Manure application is another viable option for improving soil health and metal remediation (Shumba et al. 2014; Sabir et al. 2015). Application of organic manures in Cd-contaminated soil decreased the Cd phytoavailability and resultantly improved wheat growth owing to little oxidative damage (Ahmad et al. 2011). Zhao et al. (2014) conducted a field experiment to assess the effect of long-term cattle manure application on Cd uptake by maize and soil properties. The results showed that the use of compost improved the availability of Cd in the soil and the uptake in maize, but Cd accumulation was higher in shoots compared to grains; so, it was concluded from the above study, that manure application enhanced or reduced Cd uptake and availability depending upon manure type. Thus, the choice of manure is an important step to achieve good phytoextraction efficacy by maize crop. Different organic manures when amended to soil may reduce Cd bioavailability and uptake (Rizwan et al. 2016a, b). Green manure is also very useful in improving soil fertility and Cd remediation. Ok et al. (2011) reported that the use of rapeseed residues as green manure decreased the concentration of Cd in rice plants by transferring Cd to more stable factions. In another study, combined application of lime and organic amendments in Cd contaminated soil significantly improved rice yield and decreased Cd contents in grains (Guo et al. 2018).

**Table 9** Effect of biochar application on crops growth and Cd uptake, grown on Cd-contaminated soils

| Plant specie | Feedstock | Applied rate | Soil type | Experiment type | Heavy metals | Effects | References |
|---|---|---|---|---|---|---|---|
| Rapeseed | Miscanthus (600 °C) | 1%, 5% and 10% | Sandy loam | Pot | Cd, Pb, Zn | Availability of Pb, Cd, and Zn reduced, and production of rapeseed increased | Houben et al. (2013) |
| Maize | Conocarpus tree waste (400 °C) | 0, 1, 3, and 5% w/w | Collected from mines | Pot | Pb, Cu, Cd, Mn, Zn | Pb and other metals contents decreased in shoot and moisture contents and bulk density of soil increased | Al-Wabel et al. (2015) |
| Rice | Wheat straw (350–550 °C) | 0, 10, 20, and 40 t $ha^{-1}$ | | Field | Pb, Cd | Decreased the metal availability in soil and metal contents in shoot and grains and increased the pH and organic matter of soil | Bian et al. (2014) |
| Rice | Rice straw, husk, bran (500 °C) | 5% w/w, | | Pot | Cd, Zn and Pb | Application of biochar produced from different tissues of rice plant decreased Cd accumulations in rice shoot | Zheng et al. (2012) |
| Wheat | Rice bran, straw and husk (500 °C) | 5% w/w | Clay loam | Pot | As, Cd, Pb, Zn | Reduced the available Pb, Cd, and Zn, while As availability increased. Plant biomass, growth, and soil pH improved | Zheng et al. (2013) |
| Rice | Bean stalk and rice straw (500 °C) | 0 and 20 t $ha^{-1}$ | | Pot | Cd, Pb, Zn | Reduced metal concentrations in roots, shoots, and grains of rice | Zheng et al. (2015) |
| Rice | Sewage sludge, (500 °C) | 5 and 10% w/w | Metal contaminated soil | Pot | As, Cd, Cr, Ni,Pb, Zn | Bioaccumulation of heavy metals reduced with increase in biomass and grain yield of rice | Khan et al. (2013) |
| Rice | Sewage sludge, (500 °C) | 5 and 10% w/w | Mine impacted soil | Pot | As, Cd, Mn, Zn,Cu, Pb | Reduced HM uptake and improved economical yield | Khan et al. (2014) |

**Table 9** (continued)

| Plant specie | Feedstock | Applied rate | Soil type | Experiment type | Heavy metals | Effects | References |
|---|---|---|---|---|---|---|---|
| Rice | Oil palm fibers (700 °C) | 1% w/w | Metal contaminated soil | Pot | As, Cd | The mobility and bioavailability of Cd and As in co-contaminated paddy soil reduced | Qiao et al. (2018) |
| Physic nut | Quail litter (500 °C) | 0, 5, 10, and 15 g $kg^{-1}$ soil | Loamy | Field | Cd | The concentration of Cd in physic nut reduced; greater reduction with the higher application rates | Suppadit et al. (2012) |
| Maize | Green wastes (500 °C) | 0, 1, 2.5, 5, and 10% w/w | Sandy loam | Pot | Cd, Cr, Pb | Biochar application reduced Pb and Cd toxicity by immobilizing them into more stable forms and improved the soil quality | Alaboudi et al. (2019) |
| Rice | Corn stalk, peanut hull, and rice hull (450 °C) | 0, 0.5, 1, 2. 3, and 4% w/w | Loamy | Pot | Cd | Biochar decreased the exchangeable Cd concentrations by 28.5 to 59.4% in soil and improved rice growth | He et al. (2017) |
| Rice | Wheat straw (350–550 °C) | 0, 10, 20 and 40 t $ha^{-1}$ | Metal contaminated soil | Field | Cd, Pb | Biochar soil significantly enhanced soil pH, total organic carbon and reduced soil extractable Cd and Pb | Bian et al. (2014) |
| Rice | Wheat straw, 450 °C | 0, 20 and 40 t $ha^{-1}$ |  | Field | Cd | Application of biochar improved plant biomass and reduced the amount of bioavailable Cd (34%) and Cd uptake by rice (61%) | Bian et al. (2016) |
|  | Rice straw (500 °C) | 3% w/w | Silt loam | Laboratory incubation study | Cd, Pb | Concentration of Cd and Pb in paddy soil were reduced by 17% and 30.3% respectively | Bashir et al. (2018) |

**Table 9** (continued)

| Plant specie | Feedstock | Applied rate | Soil type | Experiment type | Heavy metals | Effects | References |
|---|---|---|---|---|---|---|---|
| Lettuce | Paper mill sludge, pruned branches and distillery sludge (400 °C) | 0, 1, 2, and 5% w/w | Loamy sand | Pot | Cd, Zn | Biochar reduced the phyto-availability of Cd owing to higher pH | Kim et al. (2015a) |
| Lettuce | Rice hull (500 °C) | 0, 0.5, 1, 2, 5, and 10% (w/w) | Loamy sand | Pot | Cd, Pb, Zn | Biochar reduced the concentration of Cd and other HMs in soil | Kim et al. (2015b) |
| | Bamboo, coconut shell, pine wood shavings, and sugarcane bagasse (450 °C) | 2% w/w | Metal contaminated soil | Pot | Cd | Bamboo-derived biochar showed the highest effect on Cd immobilization in soil | Tan et al. (2015) |
| Tobacco | Ramie stick, rice straw (350–550 °C) | 0, 0.5, and 1% w/w | Red clay | Pot | Cd, Pb | The Cd and Pb reduced in soil and plant due to rise in soil pH | Shen et al. (2016) |
| Rice | Sawdust fly ash, Bagasse fly ash, rice husk ash (400–500 °C) | 1% w/w | Metal contaminated soil | Pot | Cd | Biochar application considerably reduced the Cd concentration in soil and rice grains | Suksabye et al. (2015) |
| Green gram | Cassava stem (350 °C) | 0, 5, 10, and 15% w/w | Silt clay loam | Pot | Cd, Zn | Biochar reduced the mobility of Cd in soil and improved the growth and yield | Prapagdee et al. (2014) |
| Finger Rush (*Juncus subsecundus*) | Oil mallee, wheat chaff (750 °C) | 0, 0.5, and 5% w/w | Sandy loam | Glasshouse | Cd | Biochar immobilized soil Cd and increased soil pH | Zhang et al. (2013c) |
| Rice | Rice straw | 0, 7.5, and 15 t ha$^{-1}$ | | Field | Cd | Improved grain yield and reduced Cd contents in different parts of the plant | Zhang et al. (2014b) |
| Rice | Wheat straw, 350–550 °C | 0, 10, 20, and 40 t ha$^{-1}$ | | Field | Cd, Pb | Improved paddy yield and reduced DTPA extractable Cd and Pb | Zhang et al. (2015b) |
| Common bean (*Phaseolus vulgaris* L. cv. Falguni) | Hardwood (400 °C) | 6, 12, and 18 mg kg$^{-1}$ soil | Sandy loam | Pot | Cd | Biochar substantially reduced the bioavailability of Cd | Mondal et al. (2019) |

**Table 9** (continued)

| Plant specie | Feedstock | Applied rate | Soil type | Experiment type | Heavy metals | Effects | References |
|---|---|---|---|---|---|---|---|
| Jack bean (*Canavalia ensiformis*) | sugar cane straw (700 °C) | 0, 1.5, 3, and 5% w/w | Loamy | Pot | Cd, Pb, Zn | Uptake of Cd, Pb, and Zn reduced with biochar incorporation | Puga et al. (2015) |
| | Unfertilized dates (500 °C) | 0, 0.5, 1, and 2% w/w | Sandy loam soil | Pot | Cd, Ni | Biochar application considerably reduced the Cd contents in soil | Ehsan et al. (2014b) |
| Rice | Wheat straw (450 °C) | 0, 20 and 40 t $ha^{-1}$ | Metal contaminated soil | Field | Cd | Soil pH was considerably increased (about 1 unit) while available Cd substantially reduced by a maximum of 85% after biochar addition | Chen et al. (2016) |
| Tobacco | Tobacco stalk, dead pig (450 °C -650 °C) | 0, 1, 2.5, and 5% w/w | Clay loam | Pot | Cd, Zn | Biochar from both feedstocks was effective in Cd and Zn removal and improved crop growth | Yang et al. (2017) |
| | Rice straw, bamboo (750 °C) | 0, 1, and 5% w/w | Sandy loam | Pot | Cd, Cu, Pb, Zn | Significant reduction in the bioavailability of Cd and other HMs and improved catalase activity | Yang et al. (2016b) |
| | Sugar cane bagasse, and orange peel (500 °C) | 0, 1, 2, 5, and 10% w/w | Silt loam | Pot | Cd, As | Both biochar significantly reduced the solubility of HMs and enhanced soil pH | Abdelhafez et al. (2014) |
| Bean (*Phaseolus vulgaris*) | Olive mill waste (°C) | 0, 5, 10, and 15% w/w | Sandy | Pot | Cd, Pb, Zn | Biochar reduced mobility, bioavailability, and toxicity of toxic metals and also improved the soil properties | Hmid et al. (2015) |
| Lettuce | Rice straw (500 °C) | 0, 10, and 20 t $ha^{-1}$ | Sandy loam | Field | Cd | Immobilization of Cd increased with the application of biochar | Zhang et al. (2017) |

**Table 9** (continued)

| Plant specie | Feedstock | Applied rate | Soil type | Experiment type | Heavy metals | Effects | References |
|---|---|---|---|---|---|---|---|
| Red amaranth (*Amaranthus tricolor* L.) | Poultry litter and eucalyptus (400–600 °C) | 3% w/w | Metal contaminated soil | Pot | Cd | Reduced bioavailable and mobile fractions of Cd | Lu et al. (2014) |
| Wheat | Wheat straw (485 °C) | 0, 20, and 40 t ha$^{-1}$ | Clay | Field | Cd, Pb | An increase in soil pH contributed to the reduction in Cd and Pb mobility | Sui et al. (2018) |
| Maize | Chicken manure (550 °C) | 5% w/w | Sandy | Glasshouse | As, Cs | Biochar reduced the pH and mobility and bioavailability of Cd also reduced | Rocco et al. (2018) |
| Rice | Peanut shell (350–500 °C) | 5% w/w | Acidic | Pot | Cd, Pb | The pH of soil increased with biochar application, which resulted in Cd precipitation as $CdCO_3$ | Xu et al. (2018) |
|  | Wheat straw (450 °C) | 0, 10, 20, and 40 t ha$^{-1}$ | Ferric accumulic Stagnic | Field | Cd, Pb | Exchangeable fractions of Cd and Pb were considerably reduced | Cui et al. (2016) |
|  | Malaysian palm oil board (250 °C) | 0%, 0.5% and 1% (w/w) | Metal contaminated soil | Field | Cd, Pb | Cd and Pb substantially reduced with the enhancing incubation time | Fahmi et al. (2018) |
|  | Bamboo (700 °C) | 0, 1 and 5% w/w | Sandy loam | Pot | Cd, Cu, Pb, Zn | Biochar application significantly reduced the concentration of Cd and other metals in soil | Lu et al. (2017) |
| Wheat | Rice straw (450–500 °C) | 0, 3 and 5% w/w | Sandy loam | Pot | Cd | The reduced Cd contents may be due to the enhanced concentration of organic matter | Abbas et al. (2018) |
| Canola | Rice straw (400 °C) | 0.5 and 1% w/w | Metal contaminated soil | Pot | Cd, Ni, Pb, Zn | Biochar application reduced 77% accumulation of Cd in canola shoots | Mahmoud et al. (2018) |

**Table 9** (continued)

| Plant specie | Feedstock | Applied rate | Soil type | Experiment type | Heavy metals | Effects | References |
|---|---|---|---|---|---|---|---|
| Lettuce | Rice straw (500 °C) | 0, 10, and 20 t $ha^{-1}$ | Sandy loam | Greenhouse | Cd | Application of biochar led to the transformation of soluble Cd to the stable form, specifically formation of metal (hydr)oxide, carbonate | Run-Hua et al. (2017) |
| Wheat | Mango pruning wood (500 °C) | 20 g $kg^{-1}$ soil | Sandy loam | Greenhouse | Cd | Biochar as soil amendment effectively reduced Cd stress in bread wheat and improved yield | Farooq et al. (2020) |
| Wheat (*Triticum aestivum*) | Bamboo biochar (750 °C) | 0, 0.1, 1 and 5% (w/w) | Pot |  | Cd | Cd uptake reduced in root, straw and grain | Ma et al. (2021) |
| Tobacco | Peanut-shell waste (400 °C) | 0 and 1% (w/w) | Pot | Cinnamon soil | Cd | Photosynthetic pigments, gas exchange attributes and activity of enzymatic antioxidants were increased along with a decrease in Cd absorption | Ren et al. (2021) |

**Table 10** Effect of organic amendments on crops growth and Cd uptake, grown on Cd-contaminated soils

| Plant species | Soil type | Organic amendment | Applied dose | Effects | References |
|---|---|---|---|---|---|
| Maize | Sandy | Compost | 0 and 15 t $ha^{-1}$ | Compost reduced the Cd uptake and increased the plant growth | Ahmad et al. (2015) |
| Maize | | Rice straw and cow manure | 6.25 and 12.5% (w/w) (rice straw), 10 and 20% (w/w) (cow manure) | Both the amendments improved the root and shoot biomass and grain yield. The concentration of Cd in roots and shoots reduced significantly | Putwattana et al. (2015) |
| Amaranth | Sandy loam | Farmyard manure (FYM) | 0, 10, and 20 t $ha^{-1}$ | FYM application improved the plant growth and reduced the concentration in shoots | Alamgir et al. (2011) |
| Rice | Silty clay | Compost | 0, 1, and 2% (w/w) | Compost amendment decreased the bioavailability of Cd in soil and reduced uptake of Cd in rice | Wu et al. (2011) |
| Maize | | Cattle manure | 0, 20, and 40 t $ha^{-1}$ | Application of manures increased the Cd contents in maize grains | Zhao et al. (2014) |
| Tobacco | Sandy loam | Cow manure | 1 and 2% (w/w) | Cow manure amendment reduced uptake of Cd in tobacco leaves to allowable limits and improved tobacco yield | Ngorwe et al. (2014) |
| Cucumber | Sandy | Bagasse | 3% and 5% (w/w) | Bagasse application effectively mitigate Cd toxicity and reduced mobility and bioaccumulation of Cd | Khan et al. (2018) |
| Foxtail amaranth (*Amaranthus caudatus*) | | Farmyard manure | 0.5, 2, 5 and 10% (w/w) | FYM amendment at 5% reduced the Cd load in leafy vegetable | Singh and Prasad, (2014) |
| *Amaranthus caudatus* | | Straw dust | 0.5, 2, 5 and 10% (w/w) | Application of straw dust improved the yield by improving the antioxidant system of plants | Singh and Prasad, (2014) |
| *Amaranthus caudatus* | | Rice husk | 0.5, 2, 5 and 10% (w/w) | Rice husk application significantly reduced the Cd content in tissues (23%) and improved the yield | Singh and Prasad, (2014) |
| Wheat | Sandy clay | Chicken manure | 10, 20, and 30 g $kg^{-1}$ soil | Application of chicken manure along $KH_2PO_4$ reduced the Cd availability by 63% and improved the yield | Zhang et al. (2016) |
| Rice | Sandy loam | Manure | 0, 1, and 3% (w/w) | The addition of manure enhanced soil pH and increased paddy yield with substantially reduced Cd contents | Han et al. (2011) |
| Rice | Loam | Poultry manure | 80 g/pot | Reduced Cd concentration in soil and improved plant biomass and grain yield | Ullah et al. (2017) |

**Table 10** (continued)

| Plant species | Soil type | Organic amendment | Applied dose | Effects | References |
|---|---|---|---|---|---|
| Rice | Sandy loam | Press mud | 2% (w/w) | Reduced Cd concentration by 50% in soil and improved growth, photosynthetic traits and yield of rice plants growing under Cd stress | Azhar et al. (2019) |

### 5.7.4 Press Mud

Press mud is a waste product produced after sugarcane crushing which comprises essential nutrients for plants. Press mud is an organic fertilizer that is considered a good soil conditioner (Kumar et al. 2017). The composition of press mud varies from 68–70% moisture, 24–28% combustible fraction, and 6–8% ash (Gangavati et al. 2005). Application of press mud immobilized Cd and improved the growth and yield of maize in Cd-polluted soil (Akhtar et al. 2019). Vermicomposting of press mud and fly ash significantly improved micronutrients concentration and reduced Cd and other HMs in the feedstock. Moreover, the enzymatic activities (phosphatase, dehydrogenase and urease) were increased (Karwal and Kaushik 2020). In a recent study, the application of press mud in HM polluted soil in rice–wheat system substantially reduced AB-DTPA extractable Cd in soil and improved growth of wheat (Rehman et al. 2020). In summary, organic amendments like biochar, manures, compost, and press mud might be a feasible option for remediation of Cd-polluted soils but their nutrient retention mechanisms should be kept in mind before application.

## 5.8 Remediation Potential Through Molecular Breeding and Genetic Engineering

Some plants have innate abilities to remediate HMs from soil and environment, but this remediation potential is quite slow because the rate of bioremediation is directly proportional to plant growth rate. The direct correlation of plant growth and biomass with the total amount of bioremediation makes the remediation process very slow. Therefore, there is a need for the identification of rapid growing and high biomass accumulating plants that have strong metal accumulation potential (Koźmińska et al. 2017). In this regard, genetic engineering has promisingly facilitated to modify the plants by transforming their primary and secondary metabolisms with the introduction of new phenotypic and genotypic characteristics aiming to enhance/improve their phytoremediation potential (Muszyńska and Hanus-Fajerska 2017). Success stories about the identification of genes involved in the acquisition, sequestration, translocation, and detoxification of HMs in plants and microorganisms have been widely reported (Danika and Norman 2005). Their transfer into higher biomass and fast-growing plants has been known to accelerate the process of HMs remediation (Maestri and Marmiroli 2012). Tissue culture is another potential option that can be exploited to identify the genes with higher biodegradation properties or higher metal accumulation potential to develop new varieties with enhanced tolerance and phytoremediation of HMs (Mengoni et al. 2000). For example, overexpression of gene YCF1, OsMTP1, and AtATM3 increased the accumulation and tolerance of Cd in Populus alba x P. tremula var. glandulosa, tobacco, and mustard, respectively (Bhuiyan et al. 2011; Shim et al. 2013; Das et al. 2016). It is well documented that transgenic plants have a notable ability to contribute to the revitalization of Cd-contaminated soils through phytoremediation. Further research is needed in the field of molecular breeding and transgenic approaches for the development of plants with high phytoremediation potential. Moreover, non-food crops should be selected for genetic manipulation, so that entry of toxic HMs in food items could be avoided.

## 5.9 Other Crop Practices

Tillage practices play an important role in decreasing the Cd toxicity in soil and its uptake in plants (Gao and Grant 2012). Gao et al. (2010) conducted a field study to compare the effect of conventional tillage and reduced tillage in reducing the Cd toxicity in wheat. Reduced tillage significantly decreased the Cd concentration and accumulation in wheat grains, which might be due to higher soil organic matter caused by the residue of the previous crop retained on the soil surface that can increase the adsorption and complexation of Cd. Additionally, reduced tillage may affect the microbial activity and release of Cd from crop residue (Li et al. 2017). Intercropping offers an opportunity for farmers to achieve greater production per unit land area by growing two or more crops in proximity (Chen et al. 2015). Li et al. (2009) reported in an experiment that intercropping of maize with different legumes (chickpea, alfalfa, cowpea, and purple haricot) significantly increase the Cd uptake by maize compared with non-leguminous crops (amaranth, rapeseed, and teosinte). Likewise, in a field study, the co-cultivation of maize with legumes increased Cd uptake in adjacent maize regardless of Cd levels (Liu et al. 2012), which might be due to a reduction in soil pH. Tang et al. (2012) reviewed that co-cropping with phytoextraction plants and food crops may reduce the Cd concentration and accumulation in food crops. Similarly, in rice/wheat intercropping, Cd concentration was reduced in shoots and grains of rice and wheat compared to monoculture (Wu et al. 2003). Thus, co-cropping of food crops with Cd-hyperaccumulator plants might be an option to reduced Cd concentration in food crops. Crop rotation is another alternative technique in reducing the Cd availability to crops (Yu et al. 2014). In a field study, the effect of rice rotation with oilseed rape was studied and it was observed that Cd concentration in rice grains reduced about 47% when it was rotated with oilseed rape (Wu et al. 2011). Conversely, Yu et al. (2014) carried out an experiment in alluvial loam soil under rice-rape rotation. The cultivation of rice after rape enhanced Cd concentration in rice compared with fallow treatment. This showed that oilseed rape cultivation in soil mobilized the Cd and increased the Cd uptake by subsequent rice crop. However, Cd uptake varies between cultivars of rice and rapeseed, which showed that plant species should be taken into account during crop rotation to assure food quality and safety (Yu et al. 2014). In a field experiment, it was observed that the pre-cultivation of Salix substantially reduced the Cd concentration in post-cultivated wheat grains. A high-density cultivation of Salix decreased Cd in wheat grains rapidly as compared to a low-density plantation (Greger and Landberg 2008). This showed that pre-cultivation of phytoextraction plants might be effective in reducing the Cd concentration in wheat grains. The type of soil is another important factor that determines the Cd uptake by plants. Rafiq et al (2014) conducted an experiment to study the effect of seven different textured soils on Cd availability to rice plants and results showed that Cd content in rice varied with the type of soil being highest and lowest in Periudic Agrosoils and Calcaric Regosols, respectively. Water management is an effective option in reducing the Cd uptake and accumulation in plants (Hu et al. 2013a, b; Pan et al. 2016). Limited water supply during periods of higher water requirement increased the Cd accumulation in spinach than other irrigation regimes (Tack 2017). Several studies confirmed that continuous flooding leads to reduced Cd uptake in rice plants (Hu et al. 2015). Cadmium concentration was significantly less in rice husk in intermittent and flooding treatments compared to aerobic treatments (Hu et al. 2015). In a two-year study, three different watering systems sprinkler, saturation and flooding were used for growing 26 rice genotypes. The sprinkler system diminished the average Cd content in rice between 13 and 28% than that of continuous flooding, while the saturation irrigation method caused an extraordinary increased (760% and 1000%) Cd concentration in rice. Thus, a greater amount of Cd was found in rice kernels under the saturation irrigation method (Spanu et al. 2018).

In summary, appropriate agricultural practices such as tillage, inter-cropping, crop rotation, and water management could be useful options for reducing the Cd concentration in plants.

## 6 Conclusion and Future Perspectives

Cadmium polluted soil has been well acknowledged to be a significant danger to human wellbeing by means of adulterating the food chain. Cadmium is radically harmful to agricultural harvests and accounted to diminish plant development, productivity, and quality; hence, the decline in overall yield. Moreover, Cd in exorbitant concentration triggers oxidative damages by impeding antioxidant enzymes in plants. To overcome this menace, quite a few techniques have been utilized for viable relief of Cd elicited phytotoxicity. These relief approaches chiefly include bioremediation which includes phytoremediation (phytoextraction, phytodegradation, phytovolatilization, rhizosphere degradation, rhizofiltration, phytostablization, and phytorestoration) and microbial remediation (bacteria, fungi, algae, and PGPRs). Some other recent remediation techniques for Cd decontamination are the exogenous application of chelates, PGRs, inorganic (N, P, Zn, Fe, Se, and Si), and organic (biochar, manure, compost, and press mud) amendments. Moreover, the adoption of some agricultural practices including judicious tillage, practices, crop rotation, intercropping, and water management could be sensible approaches to lighten the Cd instigated phytotoxicity. Although an enormous number of endeavors have been made to alleviate Cd toxicity in plants, further exploration ought to be carried out focusing on ensured quality as well as safe productivity of food. This ought to incorporate the following:

- Metabolomics, proteomics, transcriptomics, and genomic approaches should be needed to study for a better understanding of underlying mechanisms Cd toxicity in crop plants at the molecular level.
- More eco-friendly amendments should bring into practical exploitation for declining Cd phytotoxicity.

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**Data Availability** All data generated or analyzed during this study are included in this published article (and its supplementary information files).

## Declarations

**Ethics Approval** Not applicable.

**Consent to Participate** Not applicable.

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