# Responses and Tolerance of Cereal Crops to Metal and Metalloid Toxicity

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## Abstract

Soil acts as a sink for a number of organic and inorganic pollutants, through which these enter into the food chain and become a potential source of human diseases. Heavy metal (Cd, Cu, Cr, Fe, Ni, Pb, Zn) and metalloid (As, Sb) contamination of soil resources is increasing due to natural and anthropogenic activities. Currently, metal(loid) accumulation is one of the most serious environmental concerns owing to their toxicity to crops. Agronomic crops, mainly cereals (wheat, *Triticum aestivum*; maize, *Zea mays*; rice, *Oryza sativa*), are cultivated on large area and, thereby, are more vulnerable to metal(loid) toxicity, affecting crop growth (seed germination, root/shoot length, and biomass), physiology (water relation, pigmentation, photosynthetic machinery), and metabolic processes (reactive oxygen species (ROS), lipid peroxidation, protein degradation). However, to counter these anomalies, crops are equipped with antioxidants

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(CAT, POD, SOD, APX, GR, proline, phenolics) to detoxify metal-induced ROS and proteins (phytochelatins, PCs; metallothioneins, MTs) to sequester metal(loid)s. Thus, further insight into these processes is important to exploit better metal-contaminated areas for raising crops, generate revenue, and feed ever-increasing population. Therefore, we present an overview of heavy metal(loid) pollution in soil; their toxicity to cereals (wheat, maize, rice) at morphological, physiological, and cellular levels; and their tolerance mechanisms. At the end, we explore the symbiotic association of cereal crops to a microbe in scavenging metal toxicity.

**Keywords**
Cereal crops · Metal(loid) toxicity · Reactive oxygen species · Antioxidants · PGPB

## Abbreviations

| | |
|---|---|
| AI | acid invertase |
| APX | ascorbate peroxidase |
| AsA | ascorbic acid |
| ATP | adenosine triphosphate |
| CAT | catalase |
| CCA | copper-chromium-arsenic |
| DHAR | dehydroascorbate reductase |
| ETS | electron transport system |
| GDH | glutamate dehydrogenase |
| GOGAT | glutamine oxoglutarate aminotransferase |
| GPOD | guaiacol peroxidase |
| GR | glutathione reductase |
| GST | glutathione-S-transferase |
| HMW | high molecular weight |
| IAA | indole-3-acetic acid |
| IBA | indole butyric acid |
| MDA | malondialdehyde |
| MDHAR | monodehydroascorbate reductase |
| MT | metallothioneins |
| NAA | naphthaleneacetic acid |
| POD | peroxidase |
| SOD | superoxide dismutase |

## 14.1 Introduction

Soil contamination and metal pollution are the most imperative concerns in the industrialized world due to harmful effects on the biological system (Kisku et al. 2000). Heavy metals and metal(loid)s include cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), nickel (Ni), lead (Pb), zinc (Zn), arsenic (As), selenium (Se), and antimony (Sb) (Yadav 2010). Plants obtain the necessary and beneficial nutrients from organic matter or soil; however, the plants can also uptake and accumulate nonessential toxic metal(loid)s when these are bioavailable in soil (Kisku et al. 2000; Houshm and Moraghebi 2011). Heavy metal(loid)s are present in the soil naturally due to weathering of minerals, erosion, and volcanic activities; in addition to them, anthropogenic activities such as mining, electroplating, wood preservation, pesticides, industrial effluent, and fossil-fuel burning are also polluting our environment and thus have adverse impact on the biological entities (Alloway 2013). Heavy metals and their oxides are long persistent after their introduction and change their chemical forms with the varying bioavailability in most of cases; they do not undergo microbial or chemical degradation. Soil contamination by the heavy metals has a risk and adverse impact on human health by the direct ingestion or contact with contaminated soil, through the food chain or drinking the contaminated water (Alloway 2013; Singh et al. 2011). The main reasons for the toxicity of the metalloids are the mining process, manufacturing of the synthetic product, and their uses. Landfill sites and old orchards have a potential risk of arsenic due to excessive use of insecticide in the past for different purposes and the dumping of industrial hazardous waste or chemical waste (Alloway 2013).

Heavy metal(loid)s do not perform any known physiological function in the plants. Some metals are necessary for normal growth and required for the metabolism of the plants such as Co, Cu, Fe, Mn, Mo, Ni, and Zn, but they can harm when the concentration of any element is higher than the optimal level (Penna and Nikalje 2018; Alloway 2013; Krantev et al. 2008). The heavy metal contamination not only has an adverse impact on different constraints relating to plant quality and its yields but also alters the population size, composition, and activity of microbial community residing in the rhizosphere (Alloway 2013). Metals influenced the enzyme activities by the different approaches due to the disparate chemical affinities of the enzymes in the soil system; for example, the Cd toxicity is higher toward enzymes than Pb because it has greater mobility and lesser affinity to the soil colloids (Verma and Dubey 2003). Cr (IV) is a highly toxic and strong oxidizing agent, and its high concentration can cause harmful effects on the microbial cell metabolism (Shanker et al. 2005). Heavy metals can also affect the microbial reproduction in the composting process and cause morphological and physiological changes (Alloway 2013; Shanker et al. 2005).

Abiotic stresses such as heavy metal(loid)s, drought, salinity, water logging or flooding, and extreme temperature have adverse impacts on germination, growth, development, and seed quality of field crops; in some cases, these stresses reduced production rate up to 60% (Chapagain et al. 2017). On the other hand, global food production requirements increase day by day that would double in 2050 to meet the needs of the growing population. Hence, one of the best way to ensure food security for the future generation is to develop the various stress-tolerant crop varieties. Extensive increase in the intensity and frequency of tremendous weather event and unpredictable monsoon rainfall has caused intense and frequent cycles of drought and flood. Rising temperature causes water stress condition and heat; predominantly, regions like arid and semiarid consequentially reduce agriculture productivity. Heavy metal(loid) stress also caused a decrease in plant nutrient contents, leaf area, shoot growth, root length, dry matter production, and seed germination effects of many cereal crops such as wheat, maize, and rice (Ahmad et al. 2015; Chapagain et al. 2017). Seed germination and seedling growth of wheat and maize cultivars were reduced on exposure to Cd (Ahmad et al. 2012, 2013).

Cadmium has adverse effects on photosynthetic rate, chlorophyll content, and intracellular $CO_2$ concentration (Krantev et al. 2008; Alloway 2013). The other metals such as Ni, Cu, Mn, and Zn also reduce photosynthetic efficiency by decreasing chlorophyll pigments (Krantev et al. 2008; Penna and Nikalje 2018). Chromium inhibits cell division, severely disturbs the cell cycle, and also reduces the root growth in the plants at the cellular level (Hu et al. 2014). Different crop plants (wheat, rice, maize) are very sensitive to metal stress; thus, some plants are referred as non-accumulator plants, whereas some plants are hyperaccumulators (*Brassica* sp., *Salix* sp., *Alyssum* sp.) and are able to tolerate toxic metals at higher level. Plant species can manage metal(loid) pollution through one or combination of these mechanisms: (i) remove the toxic metal(loid)s from the soil, (ii) avoid uptake of metal(loid)s to the plant roots, (iii) minimize the competition between metal(loid)s and fundamental nutrients that are required for the growth and development of the plants, and finally (iv) prevent movement of toxic metals into shoots. The most important thing is to be identifying the heavy metal fraction, controlling reaction mechanism, and monitoring the activities of metals and their bioavailability to the plants (Penna and Nikalje 2018).

Toxicity of metals also obstructs nitrogen metabolism, which is the important physiological processes that play a vital role in the growth and development of plants (Ma et al. 2017). Nitrate metabolism, inhibition of nitrate uptake, and its transportation are severely affected by Cd, which changes the primary nitrogen assimilation processes (Benavides et al. 2005). Plants are synthesizing and secreting many hormones which can improve plant tolerance against abiotic stresses (Chapagain et al. 2017; Penna and Nikalje 2018). Toxicity of metal(loid)s affects plant growth and development directly by causing oxidative stress and cytoplasmic enzyme inhibition, and indirectly, disturb ion homeostasis in plants, and excessive reactive oxygen species (ROS) to oxidize biomolecules in the plant (Wang and Zhou 2005; Chapagain et al. 2017). Production of the ROS is due to the effect of any type of stress. Mostly, the ROS is produced in the chloroplast, peroxisomes, and mitochondria. The heavy metal accumulation is the consequence of the disruption of $CO_2$ in the chloroplast so that it reduced the electron transport chain in the photosynthetic process and production of ROS. In the plant metabolism, ROS plays a dual function under optimum concentration; they are involved in various physiological processes and act as stress sensor. The fate of ROS totally depends on the scavenging system if the ROS scavenges efficiently so that it works as a signaling molecule. If the production of ROS is much higher and cannot be regulated to the scavenging system, it becomes toxic (Wrzaczek et al. 2013; Penna and Nikalje 2018). The antioxidant mechanism protects cells from detrimental effects of ROS. The antioxidant system includes enzymatic component that consists of glutathione reductase (GR), catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), etc. The antioxidant enzymes are used for the mitigation of induced damages of metals. It is well known that ROS generation increased by metals and in response the activity of antioxidant enzymes (POD, SOD, APX) also increased (Yang et al. 2011; Penna and Nikalje 2018).

The cereal crops (wheat, maize, and rice) are staple foods in different parts of the world; therefore, in this chapter, we discuss the toxic effects of metal(loid)s to cereal crops and find out the tolerance mechanisms they have to rectify metal(loid) stress. We also identify the role of plant growth-promoting bacteria (PGPB) and cereal interaction for the alleviation of metal(loid) stress.

## 14.2 Pollution of Metal(loid)s in Soil

The terrestrial environment is the principal sink of heavy metal(loid)s coming from geogenic and anthropogenic sources (Fig. 14.1). Metalloids such as As and Se are mainly accumulated in soil through natural resources; for instance, 45,000 tons of As is released in the environment through burning of coal on annual basis; igneous rocks contributed 100 mg As kg$^{-1}$ while manganese ores 15,000 mg As kg$^{-1}$ (Bolan et al. 2014); similarly, Se-rich shales, limestones, and mudstones are the source of Se in soils found in the USA and India (Bolan et al. 2014).

Many countries in the world are poorly designed and implement the environment act; thereby, they are facing the problem of heavy metal(loid) accumulation in the terrestrial and aquatic environment. Those having frequent use of lead gasoline have the problem of Pb accumulation in air and soil (Wuana and Okieimen 2011). Lead is a toxic element, it is present in rocks (1–150 mg kg$^{-1}$), and thereby, it has been included in new European REACH Regulation (EC1907/2006) (Kushwaha et al. 2018). Some countries are using intensive pesticides (Bordeaux mixture), and phosphate fertilizer (rock phosphate) has been reported for Cu, Cd, and Pb pollution (Wuana and Okieimen 2011; Bolan et al. 2014). The mixture of copper-chromium-arsenic (CCA) is being used for preservation of wood in the USA; Cr is also frequently used for the treatment of tanneries (Bolan et al. 2014; Robinson et al. 2006). Soil irrigated with wastewater was contaminated with heavy metals (Cd 5, Co 13, Pb 21, Cr 33, Cu 43, Mn 64, and Zn 83 mg kg$^{-1}$ soil) in Lahore, Pakistan (Mahmood and Malik 2014). They further reported the health hazard impact of these metals especially Cd and Mn via consumption of leafy vegetables cultivated in metal-contaminated soils. Heavy metal(loid)s can be divided into three distinguished hazardous classes on the basis of their toxicological profile; for instance, Dutch has divided metal(loid)s on the basis of their toxicity in soil (Vodyanitskii 2016): (i) highly hazardous (Cd, Be, Se, Sb (< 1 mg kg$^{-1}$ soil)), (ii) moderately hazardous (As,

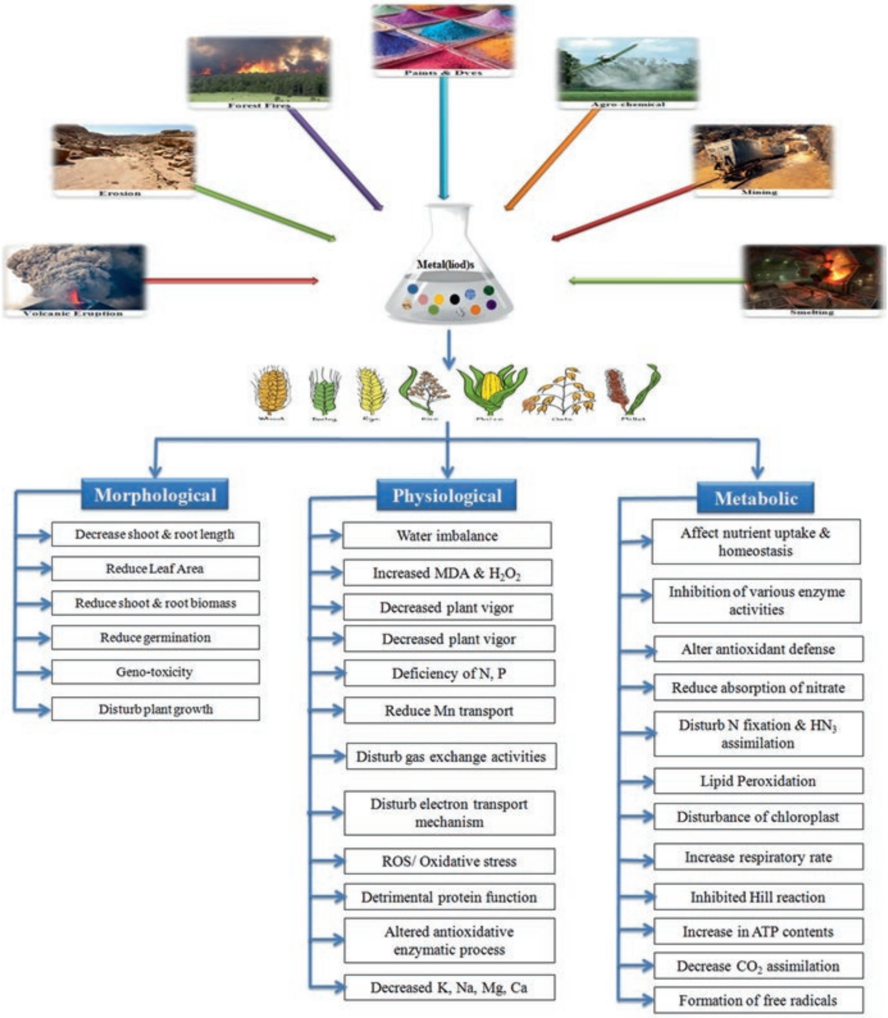

**Fig. 14.1** Sources of heavy metal(loid)s and their toxic effects on cereal crops

Ba, Cu, Cr, Hg, Ni, V (1–10 mg kg$^{-1}$soil)), and iii) low hazardous (Co, Ce, Pb, Zn (> 10 mg kg$^{-1}$ soil)). Heavy metal(loid) contamination in soils of various countries has been summarized in Table 14.1. The soils of Ghana, the European Union, and Greece were contaminated with As, whereas Bangladesh soil was contaminated with Cd higher than the values of these metals in world soil (Table 14.1). Similarly, river basin of Columbia showed higher levels of Cu, Ni, and Zn, whereas agricultural soils of Khyber Pakhtunkhwa, Pakistan, showed higher values of Zn than their respective world level (Table 14.1).

**Table 14.1** Heavy metal(loid) contamination in soils of various countries

| Sample | Country | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn | References |
|---|---|---|---|---|---|---|---|---|---|---|
| | | mg kg$^{-1}$ | | | | | | | | |
| Soil | Average Ghana | 4 | 0.052 | 21 | 6.2 | 0.32 | 3.7 | 7.2 | 39 | Bortey-Sam et al. (2015) |
| Soil | Tamso, Ghana | 27 | 0.43 | 77 | 16 | 0.42 | 28 | 14 | 118 | Bortey-Sam et al. (2015) |
| Agricultural soil | Average European Union | 4 | 0.09 | 22 | 13 | 0.04 | 18.36 | 15.3 | – | Tóth et al. (2016) |
| Soil | Dhaka, Bangladesh | – | 11 | 54 | 39 | – | 58 | 50 | 115 | Ahmad and Goni (2010) |
| River basin | Columbia | – | 0.040 | – | 1149 | | 661 | 0.071 | 1365 | Marrugo-Negrete et al. (2017) |
| Argolida basin | Peloponnese, Greece | 6.95 | 0.54 | 83 | 75 | – | 147 | 20 | 75 | Kelepertzis (2014) |
| Agricultural soil | Almería Spain | – | 0.4 | 30 | 26 | – | 27 | 26 | 66 | Rodríguez-Martín et al. (2013) |
| Agricultural soil | Piemonte, Italy | – | – | 46 | 58 | – | 83 | 16 | 63 | Facchinelli et al. (2001) |
| Agricultural soil | Huizhou, China | – | 0.10 | 28 | 17 | – | 15 | 45 | 57 | Cai et al. (2012) |
| Agricultural soil | Yongji, China | – | 0.22 | 54 | 32 | – | – | 12 | 107 | Yangchun et al. (2017) |
| Agricultural soil | Thiva, Greece | – | – | 277 | 32 | – | 1591 | 24 | 67 | Antibachi et al. (2012) |
| Agricultural soil | Zagreb, Croatia | – | 0.66 | – | 21 | – | 50 | 26 | 78 | Romic and Romic (2003) |
| Agricultural soil | KPK, Pakistan | – | – | 0.9–67 | 7–28 | – | 5–52 | – | 41–217 | Rehman et al. (2017) |
| World soil value | | 1–1.5 | 0.07–1.1 | 5–120 | 6–60 | 0.07 | 1–200 | 10–70 | 17–125 | Kabata-Pendias (2011) |

## 14.3 Metal(loid) Toxicity to Cereal Crops

Heavy metals and metalloids are ubiquitous in the environment; however, they affect crops mainly due to their contamination in soil and water. The farmers are using untreated industrial effluent to irrigate fields, chemical fertilizers, and pesticides to increase economic yield at the cost of soil pollution and quality. The exposures of heavy metal(loid)s to cereal crops are causing morphological, physiological, and metabolic changes which are elaborated here (Fig. 14.1).

### 14.3.1 Morphological Effects of Metal(loid)s

Heavy metal(loid) toxicity severely affected the plant growth and development more than any other environmental stress. Heavy metal toxicity has decreased morphological attributes of cereal crops and also caused genotoxicity. It is essential for metals to be available in sufficient amount in soil for plant uptake; once it is accumulated in plants through either H+/ATPase pump or Ca channels, it disrupts the synthesis of enzymes and proteins that inhibit seed germination and growth of plants (Kushwaha et al. 2018). They further reported that Pb toxicity also limits leaf water contents, stomatal closure, and mineral nutrients. It is reported that heavy metal (Pb) has decreased the seed germination, root/shoot length, and biomass of many cereal crops such as maize (Ghani 2010; Hussain et al. 2013; Singh et al. 2015), wheat (Yang et al. 2010; Lamhamdi et al. 2013; Ramesar et al. 2014), and rice (Gautam et al. 2010; Khan et al. 2018). Verma and Dubey (2003) examined the effect of high dose of Pb (1000 mM) to rice seedlings that caused a reduction in shoot/root length (31–40%) and shoot/root fresh weight (29–43%). Very recently, Khan et al. (2018) determined the toxicity of Pb to rice crop cultivated in nutrient-sufficient or nutrient-deficient conditions. They observed Pb toxicity to aerial part of rice; however, it did not cause any toxicity to belowground part of rice under a limited supply of essential nutrients. The short-term effects of Pb on wheat seedling were observed by Lamhamdi et al. (2011), while long-term effects were reported by Ramesar et al. (2014). They concluded that this metal has reduced seedling growth of wheat at either short- or long-term Pb exposure.

Leaf concentration determines the toxicity of Cd; Lux et al. (2011) reported that Cd causes toxicity to plants if its concentration in the leaf is $>10\ \mu g\ g^{-1}$. They also noted the toxic effects of Cd on root anatomy of the plant that is due to high accumulation of this metal in plant roots. Seed germination and initial growth stages of wheat are very crucial and sensitive to Cd toxicity (Ahmad et al. 2012, 2013). Many investigations reported that Cd has decreased root/shoot length, biomass, and chlorophyll content of cereals (Ahmad et al. 2016; Rizwan et al. 2016; Ansarypour and Shahpiri 2017). However, in some cases due to a higher concentration of Cd, crops showed phytotoxic symptoms such as browning of roots, leaf epinasty, and leaf chlorosis and necrosis (Dong et al. 2005; Lux et al. 2011). Cadmium-induced genotoxicity damages DNA, growth, and mineral uptake in plants (Benavides et al. 2005); in another study, Cd caused an acute reduction in growth, biomass, and water contents in sorghum (Roy et al. 2016).

Higher Cr accumulation may cause inhibition in seed germination and thus cause a reduction in crop growth (Adrees et al. 2015; Tripathi et al. 2015). Chromium has caused the oxidative stress in cereal crops that disturbs not only the biochemical but also the morphological functions of plants, resulting into loss of economic yield of crops (Ma et al. 2017; Handa et al. 2017). Mathur et al. (2016) examined the effects of Cr on wheat and noted that growth of wheat is inhibited due to impairment of photosynthetic and internal metabolic machinery. Wyszkowski and Radziemska (2013) reported negative effects of Cr on growth and biomass of oat.

Previous studies revealed that germinating seeds and seedling growth of rice were decreased due to toxicities of metalloids in hydroponic (Khan and Gupta 2018). Among these metal(loid)s, arsenic (As) toxicity becomes a worldwide environmental problem (Zhao et al. 2009). Zhang et al. (2016) exposed the resistant and sensitive cultivars of rice to As in a pot experiment with and without mycorrhiza. They found less accumulation of As in grains of resistant rice cultivars as compared to sensitive; however, flooding conditions promote the As accumulation in resistant cultivar when compared with aerobic conditions (Zhang et al. 2016). The authors urged the farmers to adopt these agronomic (water management) and genetic engineering-cum-breeding techniques to avoid As toxicity to rice (Zhang et al. 2016). An excellent review has been published by Islam et al. (2016a) elucidating the toxicity of As in rice. They argued that rice is more efficient at accumulating As in grains as compared to other cereals, and thereby, this is prone to relatively greater As toxicity in terms of growth and quality of rice grain. However, at the same time, the authors address some management practices to reduce As toxicity in rice. Arsenic was loaded into crop cells following the same route as followed by the essential elements and has caused morphological and metabolic effects on cereal crops (Abedin and Meharg 2002; Zhao et al. 2009). It has reported that As caused severe damage to root/shoot biomass, seed germination, and economic yield of crops (Abedin and Meharg 2002; Armendariz et al. 2016). Maize seedlings were exposed to 0–5 mg As $L^{-1}$ in hydroponics for 5 days (Stoeva et al. 2003); they observed a significant reduction in maize growth, biomass, and leaf area. Similar to other metalloids, selenium (Se) stress decreased growth and biomass of lowland rice (Mostofa et al. 2017).

### 14.3.2 Physiological Effects of Metal(loid)s

Lead (Pb) toxicity has caused a significant reduction in chlorophyll contents of wheat (Lamhamdi et al. 2013; Ramesar et al. 2014) and maize (Singh et al. 2015), and the effect was aggravated with elevated concentrations of Pb. Similarly, Zn stress significantly decreased chlorophyll a and b of wheat leaves (Li et al. 2013). It has been reported that Pb stress generated ROS in many crops (Fahr et al. 2013); consequently, it increased malondialdehyde (MDA) and $H_2O_2$ contents in wheat (Kaur et al. 2012). Similar kind of effects was reported in other studies; for example, MDA concentration has increased in maize (Gupta et al. 2009), rice (Thakur et al. 2017), and wheat (Yang et al. 2011; Kaur et al. 2012) in hydroponics under different Pb concentrations and time of exposure. The increased MDA and $H_2O_2$ contents in wheat and maize are rectified in plants by activating internal antioxidative system (Kaur et al. 2013, 2015; Singh et al. 2015). However, the ability of cereal crops to respond to Pb toxicity and detoxification mechanisms varies with growth conditions and plant species.

Cadmium ions cause inhibition in physiological machinery of cereal crops that decrease plant strength and hamper cereal crop growth (Nahakpam and Shah 2011; Ahmad et al. 2015, 2016). Leaf chlorosis, reduction in seed germination, growth and cell division, and limited uptake of water, phosphorus, and nitrogen in cereal crops are some common causes of Cd toxicity (Benavides et al. 2005; Lux et al. 2011; Shah et al. 2013). The presence of $Cd^{2+}$ is associated with the occurrence of oxidative stress (Nahakpam and Shah 2011; Ahmad et al. 2016). Also recently, it was demonstrated that $Cd^{2+}$ causes a series of ROS generation, viz., hydrogen peroxide, superoxide anion, and hydroperoxides in crop cells (Garnier et al. 2006). Effects of Cd toxicity are employed to the plasma membrane within the cell of the crop (Lux et al. 2011). $Cd^{2+}$ when taken up by the roots is moved to xylem cells through an apoplastic or a symplastic pathway for its transportation into leaves (Lux et al. 2011); however, most of this metal is restricted at roots (Ahmad et al. 2014). Such accumulation and translocation of $Cd^{2+}$ in roots to leaves differ considerably among species and even among varieties of the same species. Mostly, $Cd^{2+}$ gets deposited and binds largely in the cell walls adjacent to the plasma membrane and to the endomembrane compartments; however, in leaves, $Cd^{2+}$ is found to accumulate in vacuoles as well (Jin et al. 2015; Liu and Kottke 2004). The first visible effect of Cd toxicity was an enhancement of vacuolation in the meristematic cells and the appearance of electron-dense granules between the cell wall and plasma lemma in plant roots (Liu and Kottke 2004). At high concentration of $Cd^{2+}$, the cell death occurs owing to severe plasmolysis, shrinkage of cytoplasm, and reduction in a number of ribosomes and mitochondrial cristae (Liu and Kottke 2004).

Cr largely targeted the green pigments and photosystem and inhibited carbon assimilation in wheat (Ali et al. 2015; Mathur et al. 2016). The process of photosynthesis, enzymatic reactions, and chlorophyll (a, b, and carotenoids) content of maize were inhibited in the presence of Cr in the growth media (Islam et al. 2016b). Similar to other metals, Cr generates ROS in plants that cause specific damage, and sometimes, it spreads to whole-plant level (Anjum et al. 2014; Gill et al. 2016); this condition causes severe destruction in physiological processes of plants due to oxidative stress, which oxidizes proteins, lipids, and nucleic acid and inhibits enzymes leading to cell death in cereal crops (Adrees et al. 2015).

Selenium has generated ROS such as $H_2O_2$ and damaged cell membrane of rice plant by the production of high-lipid peroxidation that ultimately hampered the morphology of rice (Mostofa et al. 2017). ROS are considered as an indicator of stress in plants, and thus, it acts as signaling molecules (Wrzaczek et al. 2013; Luo et al. 2016). Higher concentration and accumulation of Se in crops decreased the amount of green chloroplasts and degradation of the organelles in plant root cells (Ślusarczyk et al. 2015). The increased lipid peroxidation in wheat seedlings and enhanced antioxidant activity in barley are indicators of ROS generation and accumulation in these cereals cultivated in Se-contaminated media (Akbulut and Cakır 2010; Łabanowska et al. 2012). The inhibition of green pigments, reduction in water contents, enhanced production of hydrogen peroxide, and lipid peroxidation are the major consequences of Se stress in lowland rice plant (Mostofa et al. 2017). They also noted that rice plant in Se stress showed upregulation of some antioxidant enzymes (SOD, GPX) while downregulation of others (AsA, CAT, GR). Selenium caused toxicity to cereal crops due to attachment of Se to Cys/Met complex in protein chain and resulted in formation of selenoproteins (SeCys/SeMet); this complex impairs protein functioning. The formation of SeCys complex is more detrimental to protein synthesis than SeMet, the former having more toxic nature; however, both complexes are very reactive and easily deprotonated and inhibit enzyme functions (Hondal et al. 2012). The other studies reported specific inhibition of glutathione synthesis in model plants in response to Se stress (Hugouvieux et al. 2009; Grant et al. 2011).

The As exposure to maize seedlings causes a significant reduction in green pigments that lead to lower efficiency of photosynthetic machinery (Stoeva et al. 2003); the As stress also increased lipid peroxidation and antioxidant enzyme peroxidase activity in the same plant. The As toxicity to maize seedlings is rendered due to metabolic impairment in maize cell for uptake of phosphate ions which are known analogue of arsenate ion and share the same path to enter in root cell and are transported to shoot (Stoeva et al. 2003; Smith et al. 2010). Another reason to this toxicity is the conversion of As (V) to As (III) in the cytoplasm of plant cell (Meharg and Hartley-Whitaker 2002; Stoeva et al. 2003), which causes cellular damage through generation of ROS, inhibiting enzymes and proteins (Meharg and Hartley-Whitaker 2002; Smith et al. 2010).

### 14.3.3 Metabolic Effects of Metal(loid)s

In cereal crop, toxic effects of Cd on metabolism have been observed, for instance, reduced uptake of nutrient (Sandalio et al. 2001), hampering of various enzyme activities (Obata and Umebayashi 1993), and production of oxidative stress (Romero-Puertas et al. 1999; Sandalio et al. 2001), including changes in enzymes of the antioxidant defense system (Benavides et al. 2005). Cd also decreased the accumulation of nitrate and its transport from roots to shoots, by damaging the nitrate reductase activity in the shoots of the plant. Cadmium also decreased the process of absorption of nitrogen fixation and primary ammonia in plants during Cd treatments (Balestrasse et al. 2001). Cadmium produces changes in the functionality of membranes by destroying lipid peroxidation and disturbances in chloroplast metabolism by damaging chlorophyll biosynthesis and decreasing the activity of enzymes involved in $CO_2$ fixation.

Wheat seedlings are exposed to Pb stress in hydroponics to determine its effect on nutrient uptake and metabolic products (Lamhamdi et al. 2013). They found decreased uptake of nutrients (Ca, Mg, Cu, Zn) and synthesis of proteins while increased Mn in wheat under Pb stress. Kaur et al. (2012) reported membrane instability and alteration in enzyme activities in wheat in response to Pb stress. Heavy metal stress (Ni, Cd, Pb, Zn) inhibits phosphorylation reaction and impairs electron transport system in the plant (Romanowska et al. 2002, 2006); another study reported alterations in dictyosomes, endoplasmic reticulum, and mitochondrial cristae under Pb stress (Jiang and Liu 2010). The chromosome damage and decreased in mitotic and cell division in maize cells are the consequences of Pb stress (Jiang and Liu 2000). The exposure of $C_3$ and $C_4$ plants to Pb oxidized many important substrates of Calvin cycle in mitochondria which affects respiration rate of maize and barley (Romanowska et al. 2002); moreover, Pb stress triggers ATP production in these cereals (Romanowska et al. 2002, 2006).

The scientist identified many biomarkers in plants to quantify metal stress. Among them, phytochelatins are the most common proteins produced in plants in response to heavy metals. Keltjens and van Beusichem (1998) reported the toxicity of Cd and Cu on maize and wheat metabolic activities. They observed a close association of Cd and PC contents in plant tissues; thereby, they considered PC as a biomarker of Cd stress in these cereals. Cadmium exposure to sorghum increases or decreases the expression of many proteins responsible for the metabolism of carbohydrates and protein synthesis. These factors have a major role in lowering of growth and biomass of sorghum (Roy et al. 2016). The high concentration of Zn in the growth media caused inhibition in kinase and dehydrogenase enzymes in wheat roots (Li et al. 2013); however, Zn stress does not affect hydrogen peroxide, MDA, and SOD activities in leaves of wheat. The Cu exposure to cereal crops induced metabolic and anatomical changes; for instance, it induced lipid peroxidation in wheat, maize, and rice (Adrees et al. 2015).

The high concentration of Cr decreased $NO_3$-N and increased accumulation of total N in oat (Wyszkowski and Radziemska 2013). The toxic effect of Cr on the yield of barley was also reported that was due to decreased accumulation of N compounds in this cereal crop (Wyszkowski and Radziemska 2010); interestingly, the same study compared the toxic effect of Cr on maize which showed tolerance compared to barley. This tolerance was due to greater accumulation of $NH_4$-N in maize. Exposure of plants to Cr-induced changes in their metabolic activities; in some cases, it disturbs hydrolytic enzymes (amylase) during seed germination, nitrate and nitrite reductases essential for nitrogen metabolism, and carbohydrate metabolism in plant leaves (Singh et al. 2013). The other studies also reported similar effects of Cr on nitrogen metabolism (Kumar and Joshi 2008); they observed reduced activities of urease, nitrate/nitrite reductases, glutamate synthase, and dehydrogenase in root and shoot of sorghum. Twenty-two different kinds of proteins were identified in maize exposed to Cr stress, of which six proteins were associated with sugar metabolism, three proteins were related to stress tolerance, and four were responsible for antioxidant production (Labra et al. 2006). Similarly, Ding et al. (2009) reported Cr-induced activities of protein kinase in maize, which is inactivated upon production of hydrogen peroxide scavenger. The activity of NO- and Ca-dependent kinase increased in maize exposed to Cr, and it followed the ZmMPK5 pathway for expression of these enzymes (Ding et al. 2009). Based on microarray analysis, Dubey et al. (2010) found up- and downregulation of genes in rice grown under Cr stress; these genes were involved in metabolism, transport of sugar and nutrients, and homeostasis of Cr stress by either production of antioxidant enzymes or osmolytes.

Łabanowska et al. (2012) investigated Polish and Finnish wheat seedlings exposed to Se for a two-day period. They observed increased metabolism of carbohydrates and enzymatic antioxidants in Polish than Finnish wheat that might be the reason for better Se tolerance in Polish-originated wheat cultivars. Selenium in the form of selenate is metabolized in chloroplasts via sulfur reduction process, and its toxicity is mainly due to alteration of cysteine to selenocysteine in proteins. The formation of the process of nonspecific selenoproteins in iron-sulfur clusters has reduced the rate of photosynthetic electron transport in selenate-treated wheat plants (Hondal et al. 2012). So, evidence from previous studies suggests that Se toxicity can also be increased due to the ability to catalyze the process of the oxidation of thiols and to generate ROS (Hondal et al. 2012). Selenium stress in rice plant inhibits the activity of glyoxalases and causes toxicity of methylglyoxal to rice (Mostofa et al. 2017). They also found Se toxicity on the synthesis of proteins, reducing sugars and enzymatic antioxidants in rice. Lipid peroxidation, denaturation, and disruption of many enzymes and processes in the model plant *Arabidopsis* were due to Se-induced oxidative stress (Hugouvieux et al. 2009), and moreover, it inhibits the accumulation of APX, POD, and ETS in plant cells.

Another important metalloid is As; many studies have reported metabolic-level toxicity of As in crops including cereals (Stoeva et al. 2003; Smith et al. 2010). Normally, As is transported to plant shoot, usually arsenite following the silicon while arsenate following the phosphate pathway (Meharg and Hartley-Whitaker 2002; Zhao et al. 2009; Zhu and Rosen 2009). The SH groups of proteins are mainly influenced by As, and thus, it causes conformational changes in the structure of proteins in plant cells (Van Assche and Clijsters 1990; Delnomdedieu et al. 1994). The metabolic response of six rice lines exposed to As revealed accumulation of phytochelatins in roots and grain while no production observed in leaves; instead, glutathione activity increased in leaves (Heuschele et al. 2017); similarly, As-induced lipid peroxidation and peroxidase activity were observed in maize seedlings (Stoeva et al. 2003). Studies revealed that inorganic As is converted into organic form in rice grains; for instance, Marin et al. (1992) noted that rice seedlings exposed to organic and inorganic forms of As showed that the former is a dominant species in rice grain. The summary of the physiological and metabolic effects of metal(loid)s on cereal crops is given in Fig. 14.1.

## 14.4 Responses of Plants to Heavy Metal Stress

Plants are usually immobile, and therefore, they have to face unwanted environmental variations. Cereal plants have to evolve a large number of strategies ranging from physiological and biochemical to maintain adverse effects of metal(loid) toxicity. These plants recognize stress signal and then transduce and transmit the signal into the cell and activate the response to offset the unwanted effects of stress by redesigning the biochemical processes of plant cell (Fig. 14.2). Understanding the variations in the signal transduction in plants in response to metal(loid) stress is difficult at the whole-plant level. This might be possible to monitor initial responses like

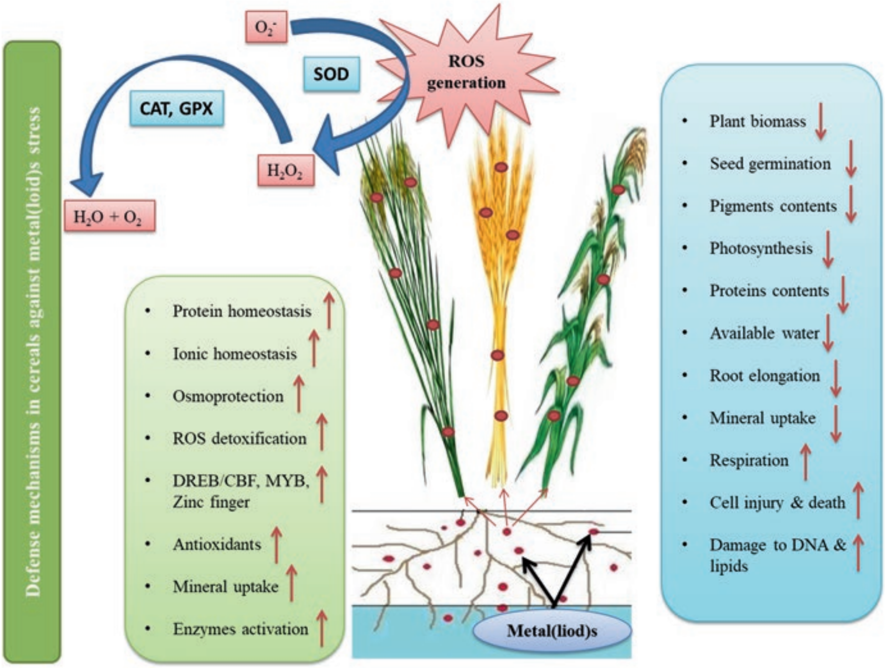

**Fig. 14.2** Possible defense mechanism activities in cereals to mitigate heavy metal(loid) stress

metabolite accumulation, oxidative stress, and transcriptomic and proteomic changes, and this will help in the recognition of changes that occur in cereal plants after heavy metal stress exposure. The similarity between heavy metals and essential plant growth elements causes competition in absorption from the soil. The presence of heavy metal(loid)s in soil competes with phosphorous and zinc and restricts their absorption from soil to plants which cause a nutrient deficiency. Heavy metal(loid)s bind with functional protein sulfhydryl group and disturb its function essential for normal plant growth and function (Lux et al. 2011; DalCorso et al. 2013; Sharma et al. 2016).

In some plants like cereal (barley), metal toxicity symptoms are similar to drought stress symptoms, and therefore, overexpression of genes related to water stress tolerance is the basic mechanism adopted by these plants that enable them to withstand metal stress (Tamas et al. 2010). Restricted seed germination and growth of seedling in wheat, decreased photosynthetic activity, chloroplast membrane damage, limited enzymatic activity, reduced plumule and radical growth, imbalanced protein metabolism, and nutrient status are the responses of cereal plants when exposed to heavy metal stress (Ahsan et al. 2010; Li et al. 2013; Ahmad et al. 2012; Ahmad et al. 2015; Singh et al. 2015, 2018). Suppression in root growth due to prolonged cell cycle and decreased cell division (decreased mitotic activity) has been reported in many cereal crops under metal stress (Jiang and Liu 2000; Kikui et al. 2005; Lux et al. 2011; Hayat et al. 2012; Anjum et al. 2014). The copper toxicity alters auxin distribution restricted root growth that causes limitation in water and nutrient uptake, and ultimately, it reduced shoot growth of cereals (Wang and Zhou 2005).

Cereal plants adopt following basic three types of mechanisms to mitigate the effects of heavy metal stress. These include physiological, biochemical, and morphological adaptations: i) Physiological adaptations are osmolyte accumulation, higher leaf gas exchange, regulation of leaf water and chlorophyll contents, and vascular development; ii) biochemical strategies utilized by plants are the regulation of antioxidant production system and biosynthesis of enzymes. These physiological and biochemical changes help the cereal plants to tolerate toxic effects of heavy metal stress and lead to iii) morphological developments like leaf development, root and shoot length improvement, leaf cell proliferation, and better seed germination and increased the fresh and dry weight of plants (Shahzad et al. 2018). The following section elaborated the salient mechanisms reported in cereals and related plant species to dilute the effect of heavy metal(loid) toxicity.

### 14.4.1 Enzymatic Antioxidants

Plants experiencing stress usually generated ROS which are hunted by the production of enzymatic and nonenzymatic antioxidants (Dat et al. 2000). The phytohormone (brassinosteroids, BRs), e.g., 24-epibrassinolide (EBL), regulates the antioxidant production system of plants and helps to tolerate metal stress (Sharma and Bhardwaj 2007; Allagulova et al. 2015; Shahzad et al. 2018). Allagulova et al. (2015) investigated the effect of EBL hormone to mitigate Cd stress in wheat. They observed dehydrin protein accumulation in wheat seedlings is responsible for Cd tolerance. Regulation of chlorophyll contents, photosynthetic activity, and osmolyte production was accompanied due to phytohormone, i.e., EBL produced by plants under metal stress to tolerate heavy metal toxicity (Hayat et al. 2007). The cereal plants adopted many defense mechanisms to mitigate metal stress: the scientists noted enhanced production of enzymatic antioxidants (SOD, APX, CAT, GPOD) in root, shoot, and leaves of wheat, maize, and rice (Kaur et al. 2012; Islam et al. 2014; Ali et al. 2015; Kaur et al. 2015; Khan and Gupta 2018) and synthesis of EBL-hormone-induced dehydrin and steroidal compounds (Allagulova et al. 2015; Shahzad et al. 2018). Superoxide radicals are mutated to $H_2O_2$ due to the action of SOD, and $H_2O_2$ is further scavenged by CAT and APX (Gill and Tutija 2010). Increase in CAT, SOD, GPX, and GSH-PX in rice and brassica was observed in response to Cr and Ni stress (Arora et al. 2010; Sharma et al. 2016). Increased nitrogen metabolism due to increased activity of nitrate reductase and nitrite reductase; increased carboxylase and oxygenase activity; and increase in activity of glutamine synthetase, glutamate dehydrogenase, glutamine oxoglutarate aminotransferase (GOGAT), and glutamate dehydrogenase (GDH) has a vital role in detoxification of toxicants produced in metal-stressed plants. Enhanced protease activity is another phenomenon that takes place to cope with heavy metal stress. Toxicity of As in rice is ameliorated by the enhanced production of antioxidants (SOD, CAT, GPX, GST) in shoot and root (Khan and Gupta 2018).

### 14.4.2 Nonenzymatic Antioxidants

Along with enzymatic antioxidants, cereal plants possess a nonenzymatic antioxidant system to combat with deleterious effects of heavy metal exposure. Ascorbic acid is an important nonenzymatic compound produced in plants under metal stress (Gill and Tuteja 2010; Hasanuzzaman et al. 2012). It is used as a reducing agent by the enzyme ascorbate peroxidase to detoxify $H_2O_2$ in the ascorbate-glutathione cycle. Furthermore, ascorbic acid improves tolerance of plants to metal stress by protecting proteins and lipids and offsets the toxic effects on growth and physiology of plants (Akram et al. 2017). These mechanisms are also observed in other plant species: for instance, enhanced activity of carbonic anhydrase and monodehydroascorbate reductase (MDHAR) of ascorbate-glutathione cycle (Hayat et al. 2007; Yadav et al. 2018). The AsA is an important nonenzymatic antioxidant to alleviate metal stress, but it is oxidized to MDHA. Thanks to nature, plants have ascorbate-glutathione cycle which converted MDHA to AsA by the hormone MDHAR in the presence of NADPH. Maintenance of AsA pool is brought about by the increased activity of this enzyme. Toxic electrophiles are produced in plants under metal stress, and increased activity of glutathione-*S*-transferase (GST) has been found to be important in detoxification of these electrophiles (Edwards et al. 2000). Upregulation of genes encoding antioxidants like DHAR, GR, GST-1, and GSH-S was observed in previous study, and overexpression of stress-related genes in plants under metal stress suggested the role of upregulation and expression level in detoxification of stress-related toxicants and in enhancing the tolerance level of plants (Ashraf et al. 2010; Zhang et al. 2015). Glutathione is also capable of reducing ROS via the ascorbate-glutathione cycle by the action of GR as it converts GSSG to GSH at the expense of NADPH (Gill and Tuteja 2010; Foyer and Noctor 2011).

Phenolics are another important group of nonenzymatic antioxidants having at least one aromatic ring (C6) bearing one or more hydroxyl groups. Biosynthesis of phenolic compounds in wheat, maize, and barley under heavy metals like Ni, Al, and Cd, respectively, has been reported (Michalak 2006). Phenolic compounds have –OH and –COOH groups which may bind metals and lipid alkoxyl radicals and limit metal-induced oxidative stress. However, this activity directly relies on the number and position of –OH group in the molecules (Michalak 2006). Various types of peroxidases (POX) are operating in the plant system of which some use ascorbate or phenol to donate an electron. These perform a vital role in lignin formation in the plant cell wall that has restricted Cd entry into the plant by developing physical barrier (Loix et al. 2017).

Organic acids like acetic and citric acid produced biologically in plants have a carboxylic group in their structure and possess the ability to chelate heavy metal ions. Citric acid mobilizes the heavy metals in the rhizosphere and facilitates the phytoremediation process (Gao et al. 2010). It has been reported that citric acid induced protection by activating host antioxidant system against metal(loid) stress (Freitas et al. 2013). Synthesis and exudation of citric acid in wheat (Tahir et al. 2015) while cysteine and proline in rice (Khan and Gupta 2018) have been reported previously to overcome the oxidative stress induced by the metal(loid)s. Amino acids like alanine, proline, cysteine, methionine, glutamine, and aspartic acid were produced in response to metal stress (Bhatia et al. 2005). Roots synthesize and deposit callose that helps them in restricting the entry of heavy metals into roots and thus avoid negative effects. Sequestration and stabilization of metals at the root level is an important strategy to avoid or protect shoot from metal-induced oxidative stress (Singh and Pandey 2011; Feigl et al. 2013). Auxin has a vital role in the improvement of root system properties like enhanced root length and root area to absorb more water and essential ions (Tahir et al. 2015). In metal-contaminated soils, cereal plants produce auxin compounds like indole-3-acetic acid (IAA), indole butyric acid (IBA), and naphthaleneacetic acid (NAA) to combat with osmotic stress caused by metal toxicity.

### 14.4.3 Protein

The activity of ATPase soluble proteins and nucleic acids mitigates the toxic effects of metal(loid) in plants (Ashraf and Foolad 2007; Choudhary et al. 2011; Madhan et al. 2014). Lipid peroxidation occurs in plants under metal stress, and plants produced membrane proteins that degrade ROS and minimize the effects of lipid peroxidation (Cao et al. 2005). Increase in free proline contents is another mechanism adopted by plants to tolerate metal stress. In the presence of elevated levels of heavy metals, plants synthesize two types of proteins, i.e., phytochelatins (PC) to chelate metal ions and metallothioneins (MT) in the cytosol for sequestration of metals in the vacuole (Hassan et al. 2017). The synthesis of S-rich proteins is known to induce stress tolerance in plants (Zagorchev et al. 2013); such kinds of proteins have been reported previously for sequestration and detoxification of metal(loid)s in plants (Clemens 2006; Viehweger 2014). In addition to heavy metal chelation and accumulation, PC also has a critical role in antioxidant production, homeostasis of metal ions, and complexation of metals with PCs (Jabeen et al. 2009; Furini 2012; Hasan et al. 2017). The heavy metal(loid)s sequestered by PC are transported from cytosol to the vacuole by ATP-dependent vacuolar pumps (V-ATPase and VPPase) and a set of tonoplast transporters (Sharma et al. 2016; Hassan et al. 2017). The advanced RNA-Seq and de novo transcriptome analysis revealed metal detoxification in plant cells is due to metal gene–encoded natural resistance-associated macrophage proteins (NRAMPs), permeases, and ATPases (Xu et al. 2015; Sharma et al. 2016; Hasan et al. 2017). Recently, Khan and Gupta (2018) identified various genes and proteins (NR, PH1, Apase, KAT1) that involved in upregulation of nutrients in rice plant under As stress. These genes along with the antioxidant defense system might involve in As detoxification in rice. In another study, various rice elite lines were screened against As stress (Heuschele et al. 2017). They found that synthesis of cysteine and phytochelatin proteins is involved in sequestration of As in rice tissue.

Metallothioneins (MT) are cysteine-rich proteins which can detoxify metal(loid)s through cellular sequestration and protection from oxidative damage (Kang 2006; Capdevila and Atrian 2011; Hassinen et al. 2011; Hossain et al. 2012; Hasan et al. 2017). The mechanism for ROS hunting is not yet clear; however, it is advocated that metals are detached from MT-metal complex and replaced with MT-ROS complex that might alleviate metal-induced oxidative stress in plants (Hassinen et al. 2011; Hasan et al. 2017). Ansarypour and Shahpiri (2017) investigated the role of rice MT isoform-OsMTl-1b against Cd stress tolerance in *Saccharomyces cerevisiae*. They conferred that isoform of MT-induced tolerance in this yeast against Cd stress. In addition to these mechanisms, proteins also have a role in repairing of damaged proteins, tolerance of endoplasmic reticulum, heavy metal stress-induced denatured proteins, and autophagy in heavy metal-stressed plants (Hasan et al. 2017).

## 14.5 Crop-Microbe Interactions Under Metal and Metalloid Stress

Around the globe, abiotic stresses like salinity drought and metal/metalloid pose a challenge to the sustainable production of crop plants (Ahmad et al. 2012; Ditta 2013; Naveed et al. 2014). In the course of time, demand for food has forced the farming community toward intensive farming which is the production of more and more crops without taking care of the health of soil-plant continuum. This farming practice has deteriorated the vital component of ecosystem, i.e., soil-plant continuum with metal and metalloids with the application of different amendments (Gajdos et al. 2012). In order to cope with this situation, several phytoremediation strategies have been employed like phytoextraction and phytostabilization (Sessitsch et al. 2013). Another strategy that could be employed is the use of rhizospheric bacteria associated with plants that are well renowned for their plant growth promotion effect under normal (Ditta et al. 2015; Ditta and Khalid 2016; Ditta et al. 2018) and abiotic stress conditions (Ahmad et al. 2012, 2013, 2014, 2016).

Plant growth-promoting microorganisms especially plant-associated bacteria, i.e., rhizobacteria, improve growth and yield of various crop plants. In literature, various researchers around the world have reviewed their role under abiotic stresses like heavy metals (Glick 2010; Ma et al. 2011; Rajkumar et al. 2012; Sessitsch et al. 2013). It has been found that these bacteria not only enhance the plant growth but also employ certain mechanisms which help increase/decrease the availability of metals and metalloids under heavy metal stress. The plant growth-promoting mechanisms include the provision of micro- and macronutrients through the production of phytohormones, siderophores, etc. (Glick 2010; Ma et al. 2011; Rajkumar et al. 2012). The mechanisms related with increasing the availability of heavy metals in the soil include the secretion of certain organic acids which lower the rhizospheric pH. The low pH is suitable for improving the availability of heavy metals in the soil and ultimately helps in phytoextraction. Similarly, solubilization of metal minerals via lowering the pH of rhizosphere by increasing the release of root exudates results in more root growth and surface area for more phytoextraction of heavy metals (Sessitsch et al. 2013; Ullah et al. 2015; Sharma and Archana 2016). With the passage of time and advancement in technology, certain bacteria have been isolated that have the ability to reduce the availability of certain heavy metals via certain mechanisms, i.e., phytostabilization and bioaccumulation. In phytostabilization, the

**Table 14.2** Plant growth promoting bacteria–induced metal stress tolerance in cereals

| Cereal crop | Metal(loid)s | Effect of bacterial inoculation on cereal crops | References |
|---|---|---|---|
| Maize | Cd | Cd accumulated primarily in the roots and transported to the shoots was rather low | Gajdos et al. (2012) |
| Maize | Cd | Plants inoculated with bacterial strains exhibited greater root-to-shoot ratio and dry biomass in Cd-contaminated soil, caused a marked increase in Cd uptake. Bacterial strains were efficient colonizer | Ahmad et al. (2016) |
| Maize | Cd | Immobilization and low translocation to the shoots reduced metal accumulation | Moreira et al. (2014) |
| Maize | Cd | Promoted root and shoot length and dry biomass | Sangthong et al. (2016) |
| Maize and wheat | Cd | Significantly reduced the suppressive effect of Cd on growth and physiology | Ahmad et al. (2014) |
| Maize and wheat | Cd | Improved growth and yield parameters through phosphate solubilization, IAA, siderophores, ACC deaminase activity | Jiang et al. (2008) |
| Maize | Cr | Enhanced Cr tolerance in maize seedlings by decreasing Cr uptake from root to shoot, reduced oxidative stress by elevating the activities of enzymatic and nonenzymatic antioxidant, improved carbohydrate metabolism under Cr stress | Islam et al. (2016b) |
| Wheat | Hg | Growth parameters and relative water content were significantly higher and vice versa for proline content, electrolyte leakage, and malondialdehyde content (shoots and roots) in inoculated plants compared to uninoculated plants under stress condition | Gontia-Mishra et al. (2016) |
| Maize | Pb | Decreased soil pH which resulted in more accumulation of Pb in shoot | Hadi and Bano (2010) |
| Maize | Pb | Improved growth and yield parameters through phosphate solubilization, IAA, siderophores, ACC deaminase activity | Jiang et al. (2008) |
| Maize | Pb | Inoculated plants had maximal growth and yield parameters, photosynthetic pigments, proline, protein, peroxidase, glutathione-S-transferase, and catalase, while these plants had minimal Pb uptake in root and shoot | Hassan et al. (2014) |
| Wheat | Zn | Inoculation improved the uptake of P and N in wheat plants with an increase in leaf chlorophyll, total soluble protein, and plant biomass production | Islam et al. (2014) |
| Wheat | Zn | Increased various growth parameters, photosynthetic pigments, Zn content in plant, various compatible solutes such as proline content (30–65%), total soluble sugar (9–49%), total protein (16–52%), and decreased the malondialdehyde (MDA) content (38–47%) as compared to control, illustrating its protective effect under metal-induced oxidative stress | Singh et al. (2018) |

(continued)

**Table 14.2** (continued)

| Cereal crop | Metal(loid)s | Effect of bacterial inoculation on cereal crops | References |
|---|---|---|---|
| Wheat | Cd, As | Significantly reduced water-soluble Cd and As concentrations, and increased pH and $NH_4^+$ concentration in the soil filtrate | Wang et al. (2018) |
| Maize | Cr, Pb | Siderophore promoted plant growth under Cr and Pb stress | Braud et al. (2010) |
| Wheat | Cd, Cr | Polymeric substances immobilized metals and decreased their uptake | Joshi and Juwarkar (2009) |
| Maize | Cu, Pb | The dry biomass of roots of inoculated plants grown with 2007 mg Cu $kg^{-1}$ and 585 mg Pb $kg^{-1}$ was increased by 28% and 20%, respectively | Rizvi and Khan (2018) |
| Barley | Cr, Co, Hg, Cd, Pb | Increased germination rate and growth parameters of barley under Cr, Co, Hg, Cd, and Pb stress | Bensidhoum et al. (2016) |
| Wheat | Cd, Cr, Cu, Mn, Ni | Inoculation decreased biological accumulation coefficient (BAC) as well as translocation factor (TF) for Cd, Cr, Cu, Mn, and Ni | Hassan et al. (2017) |
| Rice | Cd, Pb, As | Inoculation significantly improved the activities of protease and amylase, increased relative root elongation, germination percentage, root-to-shoot ratio, and overall biomass. Bacterial strains also decreased superoxide dismutase activity and malondialdehyde levels | Pandey et al. (2013) |

bacteria help in immobilization of heavy metal, thereby decreasing their availability to the crop plants (Vangronsveld and Cunningham 1998; Zhang et al. 2012). In case of bioaccumulation, there are bacteria which have the ability to tolerate certain levels of heavy metals via accumulation of metals in their cell wall (Hussein et al. 2011; Govarthanan et al. 2016). Also, there are reports about microbial biotransformation of heavy metals from one form to another nontoxic form (Qian et al. 2012; Babu et al. 2013) (Table 14.2).

Keeping in view the scope and limitations of this chapter, reports about the impact of different rhizospheric metal/metalloid-resistant and plant growth–promoting bacteria on growth and yield of rice, maize, and wheat under different metal/metalloid stresses are given in Table 14.1. Under different heavy metal stresses, inoculation with heavy metal–resistant bacteria significantly improved growth, physiological, and yield parameters of maize, wheat, and rice through phosphate solubilization, scavenging reactive oxygen species, ACC deaminase activity, and decreasing rhizospheric pH through the production of organic acids (Jiang et al. 2008; Hadi and Bano 2010; Hassan et al. 2014). More specifically, under cadmium stress, the accumulation of Cd was reduced, and plant growth and yield were enhanced with the inoculation of Cd-resistant plant growth-promoting bacteria (Jiang et al. 2008; Gajdos et al. 2012; Ahmad et al. 2014; Moreira et al. 2014; Ahmad et al. 2016; Sangthong et al. 2016).

## 14.6 Conclusion and Perspectives

Heavy metal(loid) contamination of soil is ubiquitous, and reports have confirmed their augmentation across the globe. It is a major threat for sustainable production of crops especially cereals (rice, wheat, and maize) provide food for almost 3/4 of the world population. Metal(loid)s have toxic effects on cereals starting from seed germination to maturity; these show toxic effects to cereals at morphological, physiological, and metabolic levels. The most common factor is ROS generation in cereals under metal(loid) stress; however, these crops are equipped with ROS scavenging system (i.e., production of antioxidants and proteins, mineral, and ionic regulations) to mitigate metal(loid) stress. Another tool is the application of metal(loid)-resistant microbes to cereals. They have P-solubilization, IAA, ACC deaminase, and siderophore productions which are known to mitigate metal(loid) stress through a variety of mechanisms. However, their impact authenticity remains to be explored under natural/field conditions. Moreover, there have been many reports stating concerns about the shelf life of these metal/metalloid-resistant bacteria in biofertilizers. Therefore, it would be more imperative to explore how to increase their shelf life or more special microbes having the ability to survive under natural conditions. We suggest that genetic engineering approach may prove beneficial in this regard.

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