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Morphological, physiological and biochemical responses of different plant species to Cd stress

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Abstract

Naturally plants exposed with many adverse environmental conditions like biotic and a biotic stress. Despite all others stresses heavy metal stress is one of great importance which has a notable adverse effects on crop productivity and growth, heavy metal stress triggers different responses in plants, ranging from biochemical responses to crop yield. Understanding the biochemical and molecular responses to Cd stress is essential for a holistic opinion of plant resistance mechanisms to heavy metal stress. This review illustrates some aspects of Cd stress that make changes in morphological, physiological and biochemical changes of plants. Cd stress gradually declines photosynthetic rate due to limited access of CO2 which decrease gas exchange results triggers in reduction of plant growth and productivity. It also reduce leaf size, stems extension and root proliferation and decrease water absorption and transportation by causing turgor loss through decreasing the cell wall elasticity. Exposure to Cd stress increase reactive oxygen species (ROS) production which is harmful for the cell components and toxicity of cadmium is responsible for alterations in the antioxidant systems and increase of lipid peroxidation can be strongly limited at both production and consumption level by increasing antioxidative systems. This review focuses on the ability and strategies of higher plants to respond adapt and overcome the Cd stress.

Keywords: Cd, Growth, stress, antioxidative systems, yield, lipid peroxidation

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1. Introduction

Due to detrimental effects of various biotic and abiotic stresses food productivity is decreasing all-round the globe; under changing climate to reduce these losses is a major area of concern to ensure food security. Environmental abiotic stresses, such as heavy metals, drought, extreme temperature, cold or high salinity, severely impair plant growth and productivity [1]. Many experiments described that cadmium (Cd) known as a non-essential toxic heavy metal which produced physiological and morphological alterations in plants [2] e.g. reduction in photosynthesis or growth as well as chlorosis in leaves [3].These indicators results in oxidative stress, namely increase of lipid peroxidation (LP), formation of reactive oxygen species (ROS) and decrease in the activity of enzymatic and non-enzymatic antioxidants [4-6]. Worldwide agricultural soils are slightly to considerable contaminated from heavy metals that limit the crop plants to achieve their full genetic potential and also reduce their productivity [7]. Soil pollution by heavy metals has reasonably increased in last few decades due to discharge of wastewater and waste from anthropogenic sources [8]. Mainly geological and anthropogenic activities are sources of heavy metal contamination [9]. Anthropogenic sources of metal contamination include industrial effluents, utilization of agricultural chemicals, fuel production, mining, smelting processes, military operations, small-scale industries, coal combustion and brick kilns [10,11]. In plant, cellular activities that are mostly affected by heavy metal pollution including mineral nutrition, photosynthesis, respiration, membrane structure, gene expression and other properties [12]. Plant membrane structure is first target of heavy metal toxicity [13]. The mutagenic ability of heavy metals causes DNA damage and has carcinogenic effects in animals and humans [14,15].Cadmium interferes with micronutrient homeostasis [16] and the capacity of plant genotypes to detoxify Cd can differ between and within the plant species [17,18]. Among many heavy metals Cadmium (Cd) is non -essential and harmful heavy metal pollutant which is usually released in soil [19]. Cd is widely used in the electro plating, nickel-cadmium batteries, pigment plastic stabilizer and its common sources of released include metal industry, waste incineration, combustion of fossil fuels [20]. It has been ranked among 20 toxins at number 7 which affect the human health by entering in the food chain [21,22]. Cd is a very phytotoxic metal, the plants growing on cadmium contaminated soil easily uptake the cadmium by their roots and transported to above part of plant [23,24]. It has become imperative to explain the responses and adaptation of crops to heavy metal contaminated soils and take actions to decrease the heavy metal uptake ability of crop plants and to ensure higher crop yields against unfavorable environmental stresses. This article attempted to provide an overview of morpho-physiological and biochemical responses of plants to Cd stress.

2. Morphological Responses

Heavy metal stresses cause a broad variety of plant responses, ranging from gene expression and cellular metabolism to growth and productivity.

2.1. Growth

To ensure that food supplies cope with population growth and to inform agronomic practices, there is a need of complete understanding of the processes involved in crop growth and development. Plant growth and crop sustainability under different environmental stress conditions dependents on plant vegetative and reproductive growth patterns. Plant growth is a function of complex interplay between sources and sinks limitations of the two main organs of a plant, the root system and the shoot, establishing functional equilibrium [1]. The presence of heavy metals severely affects the plant growth and development more than any other environmental stress.
Many investigations reported the inhibiting effect of Cd on fresh and dry mass accumulation, height, root length, leaf area, and other biometric parameters of plants. The following phytotoxic symptoms were observed: root browning [25], leaf epinasty [26], and leaf chlorosis [27], leaf red-brownish discolouration [28].
Heavy metals reduce growth rate of plants by affecting various parts of root metabolism such as mineral and water uptake [29]. Inhibition of enzyme activities [30], membrane function [31], oxidation and cross-linking of proteins [32], induction of DNA damage [33, 34], inhibition of cell division [35], and cell death [32], but primarily disturb cellular redox environment causing oxidative stress both in roots and leaves [32,36], that subsequently induces some of these above mentioned toxic symptoms. Cd toxicity cause detrimental effect on plant growth (height) and chlorophyll content (SPAD values) [37]. Many studies revealed the fact that Cd is sturdily phytotoxic and limit the plant growth and sometimes leads toward plant death [38]. Cd cause negative effect on plant growth and development by increasing the dry to fresh mass (DM/FM) ratio in all organs [39,40]. During ontogenesis DM/FM ratio changed and it increase in young plants is a criterion for stress response, which is indicative on whole plant level [41].

2.2. Yield

Many yield determining processes in plants respond to many environmental stresses. Yield integrates many processes in a complex way. It is difficult to interpret over the entire life cycle of crops, how plants associate and display the ever changing and indefinite processes. Grain yield is the result of the expression and union of several plant growth components. Although Cd is not essential for plant growth, its ions are taken up readily by the plant roots and translocated to the above ground vegetative parts [42]. Beyond a certain level of Cd in soil, the quality of field products gets degraded and yield of crops decreased [43].
Cd phytotoxicity is also an important problem, particularly in some highly heavy metal polluted areas, where a decline in agricultural crop productivity has been observed [44-46].

3. Physiological responses

The high internal concentrations of Cd disturb almost all physiological processes in plants [47].

3.1. Root signaling under Cd stress

Cd pollution is gaining scientific interest since Cd^{2+} is readily taken up by the roots of many plant species and its toxicity is generally 2–20 times higher from other heavy metals [48]. Cadmium can be loaded into the xylem for its transport into leaves when it is taken up rapidly by the roots. Different The quantity of Cd accumulated in roots or translocated to leaves considerably different among different species. Many plant species are very sensitive to low Cd concentrations, uptake and distribution of macronutrients and micronutrients inhibit root and shoot growth, it is the result of alterations in the photosynthesis rate [49]. In rice, the Cd toxicity has been reported which cause inhibition of seedling vigor, stunting of growth, induction in synthesis of proline and certain novel proteins and decrease in activities of many key hydrolytic enzymes [50,51].

3.2. Photosynthesis

Photosynthetic machinery directly affected by environmental stresses, mainly affect by disrupting all major components of photosynthesis including carbon reduction cycle and the stomatal control of the CO_2 supply, it also increase accumulation of carbohydrates, disturbance of water balance and peroxidative destruction of lipids [52]. Negative effect of Cd on the photosynthetic rate inhibition is due to limited access of CO_2 [53]. Due to reduced chlorophyll content and the enzymatic activity involved in CO_2 fixation cause a decrease in photosynthetic rate [54] and as well as the disturbance in the uptake and distribution of mineral nutrients in plants also affect the photosynthesis [55]. Cd toxicity has detrimental effect on plant growth (height) and chlorophyll content (SPAD values) increasing metal concentrations in the culture medium. The Cd effect on chlorophyll content became more pronounced [37]. The inhibition of photosynthesis by Cd stress decreased chlorophyll content and stomatal conductance which indirectly affect the photosynthesis [56]. It is considered that the toxic Cd also strongly affect the leaves functioning during the earlier phenophases of vegetation [57, 58]. Changes in the rate of leaf change of photosynthesis are not always similar to those of canopy photosynthesis. In Cd treated wheat plants, an increased leaf photosynthesis but decreased canopy photosynthesis was observed due to the smaller leaf area [59]. The same fact was observed in Cd treated bean plants [60].

3.3. Chlorophyll content

Chlorophyll is the most important chloroplast components for photosynthesis and as well as has a positive relationship with photosynthetic rate. In Cd treated plants, reduction occurred in chlorophyll of plants which is mainly connected to its biosynthesis [61]. When Cd applied *in vivo* it decreased the concentrations of plastid pigment. It was observed that the concentration of Chlorophyll *a* is reduced more than that of Chlorophyll *b* and carotenoids [62]. First time it was reported that Cd stress has also negative effect in tomato plants [63]. Recently inhibiting effect of Cd was observed in other species like cucumber and wheat [64] [65], bean [66] and maize etc [67, 68]. Cd effect on plastid pigments depends on leaf age and plant development: true bean leaves and young cucumber leaves are very susceptible than old leaves and cotyledons [64, 69]. On the basis of observed symptoms in response to lower concentrations of Mg and Fe in the Cd-treated sugar beet plant's leaves the lower chlorophyll concentrations was due to the deficiency of these nutrients [70]. The decline of Mg and Fe content in leaves in response to Cd stress was also observed in other plant species [71]. Chlorophyll concentrations could be lowered by the activation of enzyme degradation in *in vivo* Cd treated plants. 6-day treatment was established with 100 μM Cd in *Phaseolus vulgaris* plants, the chlorophyll concentrations and activity of the so called antioxidative enzymes such as catalase (E.C.1.11.1.6.) and superoxide dismutase (E.C.1.15.1.1.) significantly decreased while the lipoxygenase (E.C. 1.13.11.12) activity increased [72].

3.4. Water relation and Cd accumulation

In bush bean plants Cd decreased water absorption and transportation possibly by causing turgor loss through decreasing the cell wall elasticity [73]. During Cd stress, Cd induced drought stress was also observed as the transcription factor DREB2A, which is implicated in ruling of several drought and cold induced genes upregulated [74].
Dehydrins (DHNs) (Lea D11family), which are widely distributed in the plant kingdom, are accumulated during several physiological and environmental influences causing dehydration of plant tissues [75]. Several physiological processes are responsible for cadmium accumulation in plants, including Cd uptake from soil and atmosphere during maturation and translocation of xylem from root to shoot and phloem movement into grain [76]. During the early vegetative stage in mustard most of the Cd uptake occurs [77]. The difference of Cd content in grains of bread and durum wheat cultivars based on the genotypic variations in uptake by roots [78], and its transport from the root-to-shoot [79, 80]. The low level of Cd in grain was intimately connected to more Cd retention in roots [81]. External factors, such as transpiration (RH) and micronutrient cations may also aVernet Cd absorption and distribution between diVerent plant Part [82]. Cd accumulation in crop plants has direct effect on human health [83]. During heavy metal stresses, where Cd was the strongest inducer, a concentration dependent accumulation of proline was observed in roots and shoots of several plant species [84]. Cd affects uptake, transport and transpiration of water [85]. The inhibition of root growth in Cd treated plants can be easily explained by reduced water uptake. The root hydraulic conductivity into xylem vessels decreased from two to four times depending on the applied Cd stress and characteristics species [38].

4. Biochemical responses

4.1. ROS/ electrolyte leakage

Toxic effect of Cadmium on several plant species has been found and established by many researches [86] [87]. The common outcome after cadmium exposure is the increase in reactive oxygen species (ROS) production which is potentially harmful for the cell components [88] [89].
The most common indictor of oxidative damage is MDA content [90]. It also considered as an appropriate indicator for membrane lipid peroxidation. The degree of lipid peroxidation caused by ROS is a result of a considerable decrease in membrane and also incanted the occurrence of free radical reaction in tissues. The harmful effects of Cadmium on plant cells included, membrane distortion, production of reactive oxygen species (ROS) and toxic metabolites, and inhibition of photosynthesis [42, 43]. Cadmium trigger oxidative stress by tortuous mechanisms such as the induction of oxidases, interaction with the antioxidative defense, interruption in electron transport chain etc [91, 92]. Over accumulation of ROS triggers oxidative processes such as protein oxidation, membrane lipid peroxidation, enzyme inhibition and DNA and RNA damage which result in cell damage and cell death [90, 93].
The intonation of hexose and sucrose levels affects the cellular activities [94]. An increase in active mitosis is correlated with eminent ratio of hexose to sucrose, while a higher ratio of sucrose to hexose was associated with cell expansion [95]. The plants have evolved defensive mechanisms of repairing and mitigating the ROS damages to survive from Cd stress [96, 97].

4.2. Antioxidant enzymes

Plants have enzyme-catalyzed clean up system known as defensive system which guaranteeing normal cellular function by avoiding injuries of active oxygen [98], thus the equilibrium between activities of antioxidative enzyme and ROS production concluded the possibility of oxidative signaling and/or damage occurring [90]. Plants have developed a composite enzymatic and non enzymatic antioxidant system to minimize the effects of oxidative stress, such as peroxidase (POD, EC 1.11.1.7), catalase (CAT, EC 1.11.1.6), ascorbate peroxidase (APX, EC 1.11.1.11), low molecular mass antioxidants (glutathione reductase (GR, EC 1.6.4.2), ascorbate, carotenoids and ROS scavenging enzymes ,superoxide dismutase (SOD, EC 1.15.1.1) [99]. The integrity of the photosynthetic membranes maintained under oxidative stress by the cooperation of non enzymatic antioxidant [100].The enzymatic apparatus may act by producing a non enzymatic antioxidant or directly scavenge the ROS [101]. Cadmium fabricates concentration dependent variations in the antioxidant defenses of plants and stimulate oxidative stress [102]. In *Phaseolus aureus*, *Phaseolus vulgaris* and *Heliant5.hus annuus*, the alteration in the antioxidant systems and an increase of lipid peroxidation is directly related to the toxicity of cadmium [103]. Oxidative stress emerge to be engaged in Cd toxicity to judge by the decrease in some antioxidant levels and the increase of ROS (O_2^-, H_2O_2) accumulation which results slightly decrease in the CAT activities. The decrease in CAT activities is also observed in pine [104] and pea roots [102], as well as in leaves of sunflower [105] rice [106] and in leaves of *Arabidopsis* [107], while the contrary effect was observed in soybean cell cultures [108] and radish roots [109].

5. Conclusion

Heavy metal in soil is a worldwide problem seriously reducing the global crops quality and production. Heavy metal stress affects the growth, fresh to dry mass ratio and harvestable yield of crops. Leaf area, chlorophyll content, upper canopy, enzymes production, growth and development speed are pivotal indicators to determine how a plant respond to heavy metal stress.

In Cd stress, oxidative stress occurs earlier mainly during germination and plant development, Cd contents present in leaves resulted in ROS accumulation coupled with alterations in biomolecule. Transportation of Cd from stems to ears via xylem transport and phloem transport plays a significant part in Cd translocation. Other environmental conditions around the developing spikes greatly affect the transport of Cd to the developing grains.

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