Green Remediation And Physiological Responses of Plants To Metal-Contaminated Soils In Jinchang Mining Areas, Western Desert, China

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Abstract

Jinchang mining area, as a metal mine with a long history of arid and semi-arid mining in western China, has brought a great risk of heavy metal pollution to the local environment. In this experiment, tailings, slag and native soil are mixed in equal proportions for the pot experiment settings. 9 species of sand plants unique to the arid region of the western inland were planted to screen the varieties with green remediation value. After six months of plant growth, the concentration of Zn in the plant was the highest, ranging from 103.27 to 467.63mg/kg, followed by Cu, ranging from 25.07 to 200.35mg/kg. In the early stage (2 months), POD was the main defense, and in the later stage (4\6 months), SOD and CAT were the main defense, accompanied by unknown proteins up-regulated. The results of net photosynthetic rate showed that it was inhibited by metal stress in the early stage, and it was high in the late stage to provide material basis for the accumulation and secretion of adaptable and resistant substances. Seven species of plants, such as *Suaeda glauca*, *Bassia scoparia*, *Halogeton glomeratus*, *Kalidium foliatum*, *Medicago falcata*, *Atriplex canescens*, *Artemisia desertorum* can be used as enrichment materials for Zn and Cu. While, *Atriplex canescens* has the highest metal enrichment potential, and can be used as a planting variety to enrich Cd, Ni and Pb in a broad spectrum of metals including Zn and Cu. This study lays a solid scientific foundation for green remediation of contaminated soil in arid desert area of western China.

Introduction

Waste released from mines causes major environmental problems all over the world and has been the source of serious concerns in recent decades(Janette, et al. 2016). At present, the main repairing technology for soil heavy metal pollution are physical and chemical remediation(Yang, et al. 2018). These method has the disadvantages of high energy consumption, producing secondary pollution and the contaminant cannot be permanently removed(Zheng, et al. 2012). Phytoremediation is a cleanup technology for metal contaminated soils. It has advantages of lower cost, less secondary pollution opportunity and less destroy space structure etc. It still can rise to rebuild vegetation, fix landscape, and improve soil properties and soil ecological environment(Masoud, et al. 2015). At present, there are a large number of economic and industrial production activities of metal mining in western China, which caused serious land pollution of metals, mainly due to lead, copper, zinc and cadmium (Yuan, et al. 2020). In this study, sand plants were pot-planted to study their absorption and physiological response to heavy metals in the soil. Finally the plant species that could be used for green ecological restoration were selected.

Jinchang mining area, as the key area of heavy metal contaminated, produces a large amount of smelting slag and tailings in the process of metal smelting.The contents of Cu, Zn, Cr, Ni and Pb in these slag and tailings are quite high (Li, et al. 2011).Using the method of ectopic pot, the solid waste residue of tailings and slag was evenly mixed with the local farmland soil, which can dilute the metal elements in the tailings and slag, and achieve precise experimental control (Lan, et al. 2020). After plants were planted in these pots, different growth periods had different responses to external heavy metal pollutants. Plants may be more sensitive to external stimuli in the early stage of growth (seedling stage), and gradually adapt to external stimuli in the middle and late stage (flowering and fruiting stage). Peralta's research showed that the susceptibility of living alfalfa plants to Cd(II), Cu(II) and Zn(II) was correlated to the growing stage of the plants(Peralta-Videa, et al. 2004). Therefore, it is necessary to study the whole growth period when screening the desert remediation plants.

Excessive heavy metal can compel perturbations in cellular metabolism (Pandey, et al. 2002). One of the major consequences is the elevated production of reactive oxygen species (ROS) including superoxide radical ($O_2^{\cdot-}$), hydroxyl radical ($HO^{\cdot}$), hydrogen peroxide (H_2O_2), and singlet oxygen (1O_2)(Sethy S.K., et al. 2013). Superoxide dismutases (SOD) is the major O_2 scavenger and its enzymatic action results in H_2O_2 and O_2 formation. Catalase (CAT) dismutates H_2O_2 into H_2O and O_2 , which is found in peroxisomes, cytosol and mitochondria(Yan L., et al., 2010). Peroxidases (POD) decomposes H_2O_2 by oxidation of co-substrates such as phenolic compounds and/or antioxidants(Zhang FQ, et al., 2007). In heavy metal contaminated conditions, these detoxify enzymes can relieve stress toxicities and the activities can be induced simultaneously. Otherwise, The extracellular secretions, proline(PRO), glutathione(GSH) and Total Proteins(TPR), these exocrine substances can relieve the stress pressure and ameliorate oxidative damage brought by heavy metals(Tsuji N, et al, 2002). Photosynthesis was the foundation of plant metabolic process, provide plants with the organic matter, energy and oxygen, also it has a high sensitivity to environmental factors such as the heavy metal stress (Sabrine Hattab, et al. 2009). Despite numerous studies, for the endemic plant of arid northwest China, the ability of heavy metal accumulation and physiological response to the HM contamination are yet to be well described.

In this study, Potted experiment was carried out at the original mining area of Jinchang region. The raw soil (not planting, local original raw soil) was mixed evenly with the tailings and slag respectively(volume ratio 1:1). The 9 plant species endemic to western arid area (*Atriplex centralasiatica*,*Suaeda glauca*,*Chenopodium glaucum*, *Bassia scoparia*,*Halogeton glomeratus*,*Kalidium foliatum*, *Medicago falcata* ,*Atriplex canescens*,*Artemisia desertorum*) were seeds to the mixed soil pot. Along with the plant growth, the changes of physiological indexes, especially the accumulation of heavy metals in plants, during seedling stage (from seed to growth for two months), flowering stage (from seed to growth for four months) and fruit stage (from noon to the sixth month of growth) were measured. Finally, the defense characteristic values of each plant were calculated, and the plant varieties with green ecological restoration value and suitable for local planting and utilization were selected.

Method

2.1 Pot experiment:

Pot experiments were conducted under open air conditions near the Jinchang mining area, Hexi corridor, northwest China. This site belongs to the typical arid and semi-arid region, located in the north of Qilian mountains, south to Alashan terrace with low precipitation (104–129mm annually), high evaporation (1900–2100mm), and high temperatures in the summer (22°C).

The soil used in pot experiment sets was an irrigation-silt sandy soil, excavated from an oasis farm at 0-20cm depth. The irrigation-silting soils are derived from oasis/desert soils, and textures are mainly sandy. The soil sample was air dried and ground, then passed through a 10 mm sieve to remove large stones and grass debris. Without any addition, the original soil was used as the control group (CK). The mining tails from Jinchang mining area was 1:1 (v/v) mixed to the original soil as the group of treatment one (T1). While, the mining slag from Jinchang mining area was 1:1 (v/v) mixed to the original soil as another group (T2).

We choose nine plants as the endemic plants in arid and semi-arid areas. They are *Atriplex centralasiatica* (Iljin), *Suaeda glauca* (Bunge), *Chenopodium glaucum* (L.), *Bassia scoparia* (L.), *Halogeton glomeratus* (M. Bieb.), *Kalidium foliatum* (Pall.), *Medicago falcata* (L.), *Atriplex canescens* (Pursh), *Artemisia desertorum* (C.B. Clarke). These epidemic plants were seeded directly into the soil of each treatment pots. After two weeks sowing, the number of seedlings was thinned to four per pot. During the experimental period, tap water was added to compensate for evaporation and transpiration and soil moisture content was maintained at approximately 60% of water holding capacity. For each treatment(CK\T1\T2), 81 PVC pots (32 cm high, top diameter 36 cm, bottom diameter 28 cm), with holes for drainage at the bottom, were prepared, which were sufficient for three harvesting times, each with three replicates.

2.2 Determination of heavy metal contents in soils and plants

Total heavy metal concentrations (cadmium, nickel, copper, zinc, lead) in soils were determined according to national standards of China (State Environmental Protection Administration of China, 1997). The above samples were accurately weighed, then the content of heavy metals in samples was determined by atomic absorption spectrometer (Table 1)(Li, et al., 2009). The background value of heavy metal content in the mining tails and the slag was showed in Supplement Table 1. Total heavy metal concentrations(cadmium, Nickel, Copper, Zinc, lead) in the plants were extracted using the acid digestion mixture ($\text{HNO}_3\text{--HClO}_4\text{--HF}$) (EPA3010A, 1996). The clear solution obtained from the digestion was filtered and reconstituted to the desired volume for analysis using an atomic absorption spectrometer (AAS, M6MK2, Thermo Electron Corporation, USA).

2.3 Determination of the physiological performance of nine plants

SOD activity was determined by the method of Beauchamp and Fridovich (1971). CAT activity was measured according the method of Gopalachari (1963). POD activity was determined at 25°C with guaiacol (Zhang et al., 1995). The total soluble protein content was determined following the method of Bradford(1976). The content of proline was estimated spectrophotometrically according to the method described by Bates, et al.(1973). Total glutathione were extracted by homogenizing fresh leaf samples (0.4 g) with ice-cold 5 mL of 5% (w/v) m-phosphoric acid. And its concentration were measured according to Huang et al.(2010). The net photosynthetic rate of the middle and upper leaves of each plant was measured at three growth stages. LI – 6400XT portable photosynthetic apparatus was used at 8:30–11:00 at each stage.

2.4 BAC value, normalized heatmap and D value

The Biological Accumulation Coefficient (BAC) of a plant for a certain metal equals the heavy metal concentration of above ground part (including roots, stems, leaves, and grains) divided by the same metal content in soil(Li M. S. et al., 2007). The difference between treatments(T1\T2) and CK was used to measure the influence of metals in the soil on the six physiological indexes of plants. A positive value indicated that metals in the treatment soil enhanced plant physiological parameters, while a negative value indicated that metals in the soil down-regulated the physiological parameters of plants.

The six indexes(SOD,CAT,POD,TPR,PRO,GSH) of 9 plants are normalized to obtain matrices for heat map analysis. We use to normalize the physiological index matrices. The sum of the normalized values of the six physiological index parameters of each plant was defined as the defense value (D value) of the plant in response to heavy metal stress. The higher the D value represent the up regulated defense ability of the plant which affected by heavy metals in soil. On the contrary, the smaller the D value, the lower the degree of the six physiological parameters, indicate the weaker defense ability answer to heavy metals' stress in the soil.

Results

3.1 Different heavy metal content in the oasis soil of two treatment and CK pots.

From the Table 1, the results shows that five HMs(Cd, Cu, Ni, Pb, Zn) concentration(mg per kg in soil) in both T1 and T2 pot were significantly higher than the soil in CK pot. While, the soil CEC was lower in T1 and T2 than it in the CK pot. The pH were almost the same among the CK and T1, T2 pots. The concentration of Cu, Pb, Zn in T1 pot were higher than that in T2 by 55.24%, 162.72%, 169.87% respectively. While, the concentration of Cd and Ni in T2 pot was higher than that in T1 by 62.71% and 261.84%, respectively. When the tailings (T1) and slag (T2) were mixed with local native soil in equal proportions, compared with the farmland soil pollution control standard(GB15618-2018), Cd exceeded 867 (T1) -1120 (T2) times, Ni exceeded 0.6 (T1) -2.17 (T2) times, Cu exceeded 7.35 (T2) -11.41 (T1) times. Zn exceeded 15.12 (T2) -39.71 (T1) times, Pb exceeded 4.41 (T2) -11.91 (T1) times.

Table 1
Heavy metal concentration in original soil(CK) and two treatment pot(T1,T2).

	cadmium	Copper	Nickel mg/kg	Lead	Zinc	pH	CEC cmol(+)/kg
RV	0.6	100	190	170	300	>7.5	
CK	5.35	26.15	27.50	18.70	58.80	8.44	9.32
T1	312.00	1141.00	114.00	2025.00	11913.00	8.23	6.86
T2	672.00	735.00	412.50	750.35	4534.50	8.43	4.74
Notes: CK was the orial soil which sample without plants in Jinchang mining area of rural farmland; T1 was the treatment pot of mining tails mixed with the rural soil; T2 was the treatment pot of slag mixed with the rural soil. The CEC is the electrical conductivity. RV. value was the risk control standard for soil contamination of agriculture land in GB15618-2018.							

3.2 Heavy metal content in the oasis plant

Bio-accumulation factor (BAC), a ratio of heavy metals concentration in the whole plant(including roots, stems, leaves, and grains) to that in the corresponding soil at three treatment(Table 2). Of the five metals, plants tended to have stronger Cu, Zn accumulation, while for others, BACs were all below 1 except only *Atriplex canescens* (Pursh) for Cd, Ni, Pb. There were six plant species (*Suaeda glauca*, *Bassia scoparia*, *Kalidium foliatum*, *Medicago falcata*, *Atriplex canescens*, *Artemisia desertorum*) for Cu and seven species (*Suaeda glauca*, *Bassia scoparia*, *Halogeton glomeratus*, *Kalidium foliatum*, *Medicago falcata*, *Atriplex canescens*, *Artemisia desertorum*) for Zn with the BAC greater than 1.

Table 2
Multiple factors(BAC) of plants to the soil for the heavy metal content (mg/kg).

	Cadmium			Nickel			Copper			Zinc			Lead		
	CK	T1	T2	CK	T1	T2	CK	T1	T2	CK	T1	T2	CK	T1	T2
<i>Atriplex centralasiatica</i> (Ilijin)	0.03	0.02	0.08	0.06	0.06	0.10	0.04	0.26	0.46	0.02	0.39	0.62	0.01	0.02	0.10
<i>Suaeda glauca</i> (Bunge)	0.01	0.25	0.08	0.03	0.48	0.14	0.02	1.59	0.26	0.01	9.37	0.31	0.00	0.50	0.07
<i>Chenopodium glaucum</i> (L.)	0.02	0.03	0.04	0.08	0.12	0.10	0.32	0.43	0.62	0.47	0.52	0.60	0.02	0.08	0.19
<i>Bassia scoparia</i> (L.)	0.00	0.28	0.07	0.01	0.41	0.12	0.01	0.96	1.05	0.01	1.78	1.15	0.00	0.21	0.29
<i>Halogeton glomeratus</i> (M. Bieb.)	0.01	0.11	0.02	0.02	0.19	0.05	0.02	0.98	0.20	0.01	1.10	0.32	0.00	0.20	0.04
<i>Kalidium foliatum</i> (Pall.)	0.13	0.02	0.17	0.04	0.32	0.52	0.06	1.27	1.83	0.14	2.31	3.48	0.02	0.21	0.20
<i>Medicago falcata</i> (L.)	0.01	0.04	0.39	0.03	0.09	0.69	0.06	1.49	0.10	0.04	2.13	0.19	0.01	0.01	0.32
<i>Atriplex canescens</i> (Pursh)	0.03	1.06	0.06	0.05	1.30	0.17	0.08	2.51	0.40	0.04	6.36	0.82	0.02	1.25	0.11
<i>Artemisia desertorum</i> (C.B. Clarke)	0.26	0.33	0.36	0.44	0.51	0.50	0.33	1.33	0.93	0.48	2.48	1.67	0.22	0.33	0.32
Notes: The data with a BAC value greater than 1 are shown in bold.															

The heavy metal concentrations of the nine plants enriched were presented in Table 3. Cadmium concentration in the plants varied from 1.20 to 50.51 mg/kg, with the maximum value in the *Atriplex canescens* (Pursh) from T1 treatment. Nickel concentration in the plants varied from 1.56 to 32.49 mg/kg, with the maximum value also in the *Atriplex canescens* (Pursh) from T1 treatment. Lead concentration in the plants varied from 0.32 to 37.28 mg/kg, with the maximum value still in the *Atriplex canescens* (Pursh) from T1 treatment. Furthermore, there were great variations of metal concentrations among plant species and pot treatment with Copper from 7.20 to 200.05 mg/kg, Zinc from 8.93 to 467.63 mg/kg, respectively. The *Suaeda glauca* (Bunge) (Cu-25.07, Zn-178.78 mg/kg), *Bassia scoparia* (L.) (Cu-31.62, Zn-103.27 mg/kg), *Halogeton glomeratus* (M. Bieb.) (Cu-39.75, Zn-211.08 mg/kg), *Kalidium foliatum* (Pall.) (Cu-45.77, Zn-296.85 mg/kg), *Medicago falcata* (L.) (Cu-88.82, Zn-291.60 mg/kg), and *Artemisia desertorum* (C.B. Clarke) (Cu-35.67, Zn-256.42 mg/kg) also contained high amounts of Cu and Zn, respectively.

Table 3
Heavy metal concentrations enriched from pot soil of the 9 plants(mg/kg).

	Cadmium in plants(mg/kg)			Nickel in plants(mg/kg)			Copper in plants(mg/kg)			Zinc in plants(mg/kg)			Lead in plants(mg/kg)		
	CK	T1	T2	CK	T1	T2	CK	T1	T2	CK	T1	T2	CK	T1	T2
<i>Atriplex centralasiatica</i> (Iljin)	1.20	4.20	10.28	1.58	5.13	9.39	10.67	13.8	19.87	12.46	25.04	29.60	0.48	6.58	3.72
<i>Suaeda glauca</i> (Bunge)	4.11	8.23	6.22	3.23	9.22	8.09	24.36	25.07	26.67	15.80	178.78	169.21	4.85	10.43	6.18
<i>Chenopodium glaucum</i> (L.)	0.97	4.59	1.87	1.56	2.31	2.06	7.20	8.30	23.61	13.23	23.8	81.59	0.32	6.62	0.86
<i>Bassia scoparia</i> (L.)	1.56	11.25	5.44	1.64	6.25	8.93	13.35	23.92	31.62	8.93	103.27	93.54	3.73	7.01	7.74
<i>Halogeton glomeratus</i> (M. Bieb.)	2.11	3.53	3.53	2.53	3.33	4.53	11.31	29.31	39.75	13.98	211.08	55.67	1.95	7.62	8.04
<i>Kalidium foliatum</i> (Pall.)	2.49	7.27	13.55	2.55	3.24	6.81	19.43	45.77	22.99	12.94	151.00	296.85	0.73	8.96	3.53
<i>Medicago falcata</i> (L.)	1.43	15.28	12.54	3.72	12.05	12.63	12.88	88.82	58.40	7.98	291.60	43.60	0.79	7.94	13.08
<i>Atriplex canescens</i> (Pursh)	1.83	50.51	20.69	5.64	32.49	17.37	16.88	200.35	95.63	15.56	467.63	75.47	5.36	37.28	14.68
<i>Artemisia desertorum</i> (C.B. Clarke)	6.41	8.83	5.24	5.44	6.24	8.05	18.75	35.67	31.62	10.27	256.42	145.80	2.74	9.22	6.64
Note: Data in bold represents high amount of metallic elements and high bioconcentration factor.															

3.3 Physiological indices and defense ability in nine species of plants

When the 9 potted plants grew to 2 months old, the results of measured physiological indexes showed that all the other 8 plants except *Medicago falcata* increased POD activity in response to metal stress(shown in the red module in the figure).Instead of activating the oxidase system, *Medicago falcata* secretes the extracellular substance glutathione in response to the stress from metals in the soil (Fig. 2a).

When the 9 potted plants grew to 4 months old, SOD activity replaced POD and became the main antioxidant enzyme of the 9 plants in response to metal stress (Fig. 2b). *Chenopodium glaucum* secretes glutathione in response to metal stress in addition to activating SOD enzyme activity.*Kalidium foliatum* and *Artemisia desertorum* increased SOD activity, but also activated CAT and POD oxidase activities.

When the 9 potted plants grew up to 6 months old, compared with more extracellular antioxidant enzyme activities,the 7 plants secrete more exocrine substances such as the total proteins(TPR), used to resist the metal stress (Fig. 2c).

While the *Medicago falcata*, *Chenopodium glaucum* were more likely to use the antioxidant enzyme, SOD→POD to resist the metal stress (Fig. 2c).

According to the 6 physiological index parameters of the 9 plants, the difference between the treatment group and the control group was calculated, and the normalized operation was carried out. Finally, the D value of the defense ability of the 9 plants under metal stress was obtained (Table 4). From low to high, they were *Medicago falcata* (L.), *Chenopodium glaucum* (L.), *Atriplex centralasiatica* (Iljin), *Halogeton centralasiatica* (M. Bieb.), *Suaeda glauca* (Bunge), *Atriplex canescens* (Pursh), *BassiaScoparia* (L.), and*Kalidium foliatum* (Pall.), *Artemisia Desertorum* (C.B. Clarke).

Table 4. Defense value of the nine plants

	D value
<i>Medicago falcata</i> (L.)	-2.18
<i>Chenopodium glaucum</i> (L.)	-0.90
<i>Atriplex centralasiatica</i> (Iljin)	2.47
<i>Halogeton glomeratus</i> (M. Bieb.)	3.14
<i>Suaeda glauca</i> (Bunge)	3.70
<i>Atriplex canescens</i> (Pursh)	4.46
<i>Kalidium foliatum</i> (Pall.)	5.21
<i>Bassia scoparia</i> (L.)	5.24
<i>Artemisia desertorum</i> (C.B. Clarke)	6.69

3.4 Net photosynthesis rate of nine oasis plant

The results showed that under the influence of heavy metals in the soil, the net photosynthetic rate of each psammophyte at the seedling stage decreased significantly (Fig. 2). Central Asian *Atriplex* decreased by 24.09% (T2 sample). *Suaeda salsa* decreased by 16.85% (T1 sample) and 69.38% (T2 sample). *Ceratoides* decreased by 30.74% (T1 sample) and 51.59% (T2 sample). Decreased by 25.04% (T1 sample) and 48.89% (T2 sample). Halophyte decreased by 27.69% (T1 sample) and 72.81% (T2 sample). Salt claw decreased by 23.87% (T1 sample) and 19.64% (T2 sample). Wild alfalfa decreased by 32.93% (T1 sample) and 41.38% (T2 sample). *Atriplex tetraloptera* decreased by 12.56% (T1 sample) and 12.43% (T2 sample). *Artemisia annua* decreased by 30.82% (T1 sample) and 35.63% (T2 sample). The photosynthetic rate of the 9 species decreased by 12.56–32.93% in T1 samples and 12.43–69.38% in T2 samples, with the lowest decreases occurring in *Atriplex tetraloptera*.

After two months of growth, the plant reached the flowering stage, and the overall photosynthetic rate decreased compared with the seedling stage. However, different from the seedling stage, the photosynthetic rate of plants in the soil samples T1 and T2 containing heavy metals in August was higher than that in the soil samples CK without heavy metals. In general, T1 samples were 22.63–82.83% higher than CK, T2 samples were 11.28–186.27% higher than CK, and T2 was 18.21–390.59% higher than T1.

Similar to the photosynthetic situation of the plants in the flowering stage in August, after 4 months of growth, the photosynthetic rate of the plant samples in the soil affected by heavy metal pollution was still higher than that in the soil samples not affected by heavy metal pollution. In general, T1 samples are – 2.95–152.95% higher than CK on average, T2 samples are – 1.52–129.10% higher than CK on average, and T2 is 1.47–150.60% higher than T1. (The significant level is that, compared with CK, the increase in T1 is %, and that in T2 is %)

Discussion

In the present study, the pot experiment were set near the mining factory. Total 81 pot sets and 9 kinds of oasis plants were planted in three kinds of treatment (CK\T1\T2). The metal concentration of the mixture soils, tailings with the local original soil and slags with the local original soil, coupled with the concentration in the plants growing to 6 month were all determined with flame atomic absorption spectrometry. As the results illustrated, compared with the farmland soil pollution control standard (GB15618-2018), five species of metals measured almost all exceeded the control standard (Table 1). And the concentration of Pb\Cu\Zn were at the same level compared to the results of the copper-zinc, lead-zinc mine in Aletai, Xinjiang province of the China (Liu Z et al., 2016). So the metallic concentration in the area soil may be the general level for the arid and semi-arid region in the west China country.

From the metallic concentration, we calculated the BAC value of the nine plants corresponding the three treatment (Table 2). The results shows that there were six plant species (*Suaeda glauca*, *Bassia scoparia*, *Kalidium foliatum*, *Medicago falcata*, *Atriplex canescens*, *Artemisia desertorum*) for Cu and seven species (*Suaeda glauca*, *Bassia scoparia*, *Halogeton glomeratus*, *Kalidium foliatum*, *Medicago falcata*, *Atriplex canescens*, *Artemisia desertorum*) for Zn with the BAC value greater than 1. So these six plants were identified as the phytoaccumulation plant species for the Copper and Zinc. The determination Cu and Zn concentration from these plant body in the finally growing seasons were further confirmed that they are metal accumulator, especially for the Zn (Table 3). Zhang et al. (2018), Chen et al. (2014), Guo et al. (2016) also found the *Suaeda glauca*, *Chenopodium glaucum*, can be good phytoremediation plant in metal contaminated soils. For the other three kinds of heavy metals determined in the experiment, Cd\Ni\Pb, the *Atriplex canescens* was the single one species with the BAC value greater than 1. Hence for these desert plants in arid areas of western China, most plants tended to hyperaccumulate the metallic species of Cu and Zn. While the plant *Atriplex canescens* can be used as a spectral metal-enriched material with great green restoration value.

In order to preliminarily explore the tolerance of these western desert plants to heavy metals in the soil, we measured some physiological indexes. They included antioxidant enzyme system (SOD, CAT and POD), and exocrine substances (total protein, proline and glutathione content). To counteract the toxicity of ROS aroused from heavy metal stress, plants developed a complex protection system consisting of both antioxidative enzymes and non-enzymatic low-molecular-mass antioxidants. In this experiment the western desert plant physiological parameters (Fig. 2) shows that compared with exocrine substances, antioxidant enzyme system are preferred by plant to priming the resistance of heavy metal stress (as show in Fig. 2, that the more patches with red color). This results was consistent with the former researchs on two desert plant, *Peganum harmala* and *Halogeton glomeratus* (Yan L. et al., 2010).

Initially we thought that the defense ability of the plant can represent the opposite ability of plants to absorb heavy metals, that confirmed from the antioxidative enzymes and exocrine substances. As the method mentioned we calculate the D value from the defense system of the plant (Table 4). According to this hypothesis, the lower of the plant D value, the more easily for the plant to extract the heavy metals from the soils. But in the final results of metal concentration (Tables 1 and 2) showed that the hyper-extracted plant, *Atriplex canescens* (Zn-BAC = 6.36), *Suaeda glauca* (Zn-BAC = 9.37), *Kalidium foliatum* (Zn-BAC = 3.48), *Artemisia desertorum* (Zn-BAC = 2.48) did not have the lowest D value. On the contrary, these plants may also have higher D value, for example, the *Kalidium foliatum* and *Artemisia desertorum* have the D value of 5.21 and 6.69, almost the highest in the tested 9 plants (Table 4). This phenomenon demonstrated that the defence system of the plant do not represent the absorption and accumulation ability of the plant. The higher metal accumulator may have certain proteins or ion channels to facilitate the heavy metal uptake and stored in the its body cells. If a suitable protein system is found, the potential of the plant to absorb and store heavy metals can be directly quantified at the molecular level. Sun et al. (2014)'s study on the *Atriplex canescens* found a heavy metal-associated protein, AchMA1 under multiple metal stree treatment (Fe, Cu, Ni, Cd or Pb). This protein can be membrane-localized and initially mediates the detoxification of heavy metal iron. That may be the reason why *Atriplex canescens* can be the spectral metal-enriched materials.

Another reason why the D value hypothesis is not valid were as follow. Heavy metals in the pot soils up-regulated the antioxidative defense mechanism in metal stressed plants and it could be used as an effective mean for the induction of metal tolerance in these plants for better growth and phytoremediation (Zhu Y et al., 2020). The ameliorating effects of heavy metals on plants were associated with enhanced activities of antioxidative enzymes (SOD, POD and CAT) and more accumulation of GSH and proline that resulted in reduced lipid peroxidation (lower content of MDA) and less accumulation of H₂O₂ (Marta M. et al., 2011). For example, some hyper-accumulators have the tendency to uptake/remove abundance of Cd from the soil, but their physiological and biochemical processes still function properly. This could be because of the high antioxidant enzyme activities, which keeps these hyper-accumulators alive even in the most unfriendly environment (Kumchai J et al., 2013). Photosynthesis was down-regulated at the initial stage due to the influence of adverse external environment, as shown in Fig. 2a. Then, as the crops grow to the middle and later stages, they gradually adapted to stress, and the products of photosynthetic metabolic pathway continued to act as basic materials supplement for the synthesis of antioxidant enzymes and extracellular substances. Also, the product was act as the fundamental energy suppliers. Therefore, the reaction on the net photosynthetic rate characteristic map (Fig. 2) was upregulated by the effect of treatment.

Declarations

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Figures

Figure 1

The strength of Antioxidase activity and amount of Extracellular material varied within 9 plant during three growing period. (a) Measured at 2 month of 9 plant growing; (b) Measured at 4 month of 9 plant growing; (c) Measured at 6 month of 9 plant growing

Figure 2

Net photosynthesis rate of nine plants during three growing stages.

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