EFFECTS OF CADMIUM AND ZINC ON GROWTH AND METAL ACCUMULATION OF *Mathiola flavida* BOISS

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Abstract

The effects of cadmium (Cd), Zinc (Zn), and Cd–Zn on growth and their accumulation in the *Mathiola flavida* shoots were investigated. A factorial experiment with two factors (Cd and Zn) concerning four concentrations of Cd (0, 5, 10 and 20 mg L⁻¹) and four Zn concentrations (0, 10, 20 and 40 mg L⁻¹) were carried out. The shoot and root biomass of *M. flavida* growing in Cd-Zn medium decreased significantly (p<0.01) compared to the control. Growing in the presence of 20 mg L⁻¹ Cd and 40 mg L⁻¹ Zn, resulted in the highest decrease of root and shoot biomass and tolerance index compared to that at 5 mg L⁻¹ Cd. At the highest Cd (20 mg L⁻¹) and Zn (40 mg L⁻¹) concentration, plant tolerance index was inhibited by 82 and 74%, respectively (P<0.01) compared with the control. The concentrations of Cd and Zn in the shoots of *M. flavida* were increased with increasing Cd and Zn concentration in the medium. Significant inhibitory effects of Zn on Cd concentration in the shoots occurred at levels above 10 mg Zn L⁻¹. On the other hand, the shoot Cd concentration of *M. flavida* in the combined Cd and Zn treatment group was reduced by 67.6%, relative to that of the Cd alone treatment group. Zinc concentrations in the shoots decreased with increasing rates of applied Cd. Therefore, we recognize *M. flavida* as a candidate for remediation of sites co-contaminated by Cd and Zn purposes in Iran, the more so because they are adapted to the local climate and soil conditions.

Key words: Cadmium, Interaction, *Mathiola flavida*, Phytoremediation, Zinc

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1. Introduction

The study of toxic heavy metal contamination in soils and crop plants is of major importance due to their health effects on humans and other animals (Pavel et al., 2012; Perfus-Barbeoch et al., 2002; Zheng et al., 2007). Cadmium (Cd) is highly toxic to humans, animals and plants. In plants, Cd exposure induces various symptoms of phytotoxicity due to its high mobility and severe toxicity (Gomes-Junior et al., 2006; Traina, 1999). Zinc (Zn) is a micronutrient essential for plants but can be highly toxic when present at excessive concentration, causing reduced growth, leaf chlorosis, and nutritional disturbances (Kinraide et al., 2004). Cadmium and Zn are elements having similar electronic configuration and valence and hence similar environmental properties. Zinc is often associated with Cd, and the processing and subsequent release of Zn to the environment is normally accompanied by Cd (Goyer, 1997; Verougstraete et al., 2003). Thus there is a real need for analysis of the adaptive ecophysiology, biochemistry and reliable technologies of Cd - Zn interaction in the environment (Duruibe et al., 2007).

Phytoremediation i.e., the use of plants to remediate contaminated soil or to render them harmless has been proposed as an environment friendly and cost-effective technique for soil and water remediation (Garbisu and Alkorta, 2001; McGrath and Zhao, 2003; Salt et al., 1998). Heavy metal uptake, translocation, and cellular sequestration are key factors of plant’s hyperaccumulation and
tolerance of heavy metals. Root system is the main interface of ion exchange between plants and their environment (Goyer, 1997; Veroustraete et al., 2003). In phytostabilization, root-accumulating plants are used to reduce the mobility of metals in sediments, and it has been demonstrated to be an economically feasible method of treating polluted land (Fritioff and Greger, 2003). Interactions among the co-exist elements occurring at root surface and within the plant affect uptake and translocation (Aravind and Prasad, 2005). The association of cadmium and zinc in the environment and their chemical similarity can lead to interaction between cadmium and zinc during plant uptake, transport from roots to aboveground parts, or accumulation in edible parts.

The interaction between metals like Cd and Zn is varied and can be difficult to predict. For example, in Phaseolus vulgaris L., the effect of Cd on the accumulation of Zn depended on the tissue concentrations of Zn. It was higher in roots and lower in shoots when Cd was added to solution culture (Chaoui et al., 1997). The interaction may also depend on the nutritional status of the plant. Addition of Cd to Zn-deficient soil resulted in reduced concentrations of Zn in Triticum aestivum L. and Triticum turgidum L. var durum, whereas the addition of Cd to soils with adequate Zn either stimulated or had no effect on the uptake of Zn (Köleli et al., 2004). Pandar et al. (2004) found a similar effect for Brassica juncea (L.) grown in Cd-contaminated soils, but Zn induced reduction in accumulation of Cd occurred only in soils supplemented with up to 340 mg Zn per kg soil; a higher dose of Zn (705 mg kg\(^{-1}\)) stimulated Cd-accumulation. It is reported that, some other crops from the Brassicaceae family (cauliflower, kale and cabbage) can also take up more metal than other plant species without visible toxicity symptoms (Zayed and Terry, 2003). Another study found no interaction between the two metals for Glycine max (L.) grown in Cd and Zn-amended soil (White and Chaney, 1980). Hart et al. (2002) determined that Zn and Cd are transported by a common carrier at the root plasma membrane, which has a higher affinity for Cd than for Zn. Therefore, Cd and Zn ions should experience competitive inhibition.

Matthiola flavida (Boiss.) is a species belonging to Brassicaceae which grows in the old Pb/Zn mining areas of central Iran (Irankouh), and has been identified as a new Zn/Pb-accumulator (Ghaderian et al., 2007). This plant has also exceptional abilities to tolerate and accumulate high concentrations of Pb, and the characteristics of rapid growth, asexual propagation, and perennial growth makes it an ideal plant for studying mechanisms responsible for accumulation as well as for the phytoremediation practices (Ghaderian et al., 2007). The objectives of this study were to investigate the interaction of Cd and Zn on the growth parameters of M. flavida including biomass production, tolerance index, and difference in Cd nd Zn uptake and translocation.

2. Material and methods

2.1. Plant culture

The seeds of M. flavida were collected from plants growing on old Pb/Zn mine area in Irankouh during June to August 2006. The Irankouh area, located in Central Iran, is a vast mountainous region with mineralized soils and several active zinc and lead mining and smelting sites (Ghazban et al., 1994). The seeds were surface sterilized and then germinated in 9 cm diameter perlite pot at 24°C for 4 days. The uniform seedlings were feeding with modified 10% Hoagland nutrient solution containing: 0.2 mM KH\(_{2}\)PO\(_4\), 0.8 mM Ca(NO\(_3\))\(_2\), 4H\(_2\)O, 1 mM KNO\(_3\), 0.4 mM MgSO\(_4\), 7H\(_2\)O, 15 µM FeEDDA, 10 µM H\(_3\)BO\(_3\), 3 µM MnCl\(_2\), 4H\(_2\)O, 0.2 µM ZnSO\(_4\), 7H\(_2\)O, 0.2 µM CuSO\(_4\), 5H\(_2\)O, 0.1 µM Na\(_2\)MoO\(_4\), 2H\(_2\)O. Nutrient solution pH was adjusted daily to 5.8 with 0.1M NaOH or 0.1M HCl, moreover, MES-KOH was used for pH adjustment. Plants were grown in growth room with 16/8 h light/dark cycles, day/night temperature of 26/20°C and light intensity approx, 280mmol m\(^{-2}\)s\(^{-1}\). The nutrient solution was renewed every 3 d.

2.2. Treatments

Pre-cultured seedlings of the M. flavida were used for different Zn and Cd treatment. There were 48 pots with 4 plants in each. After 15 d of growth in basal nutrient solution, plants were exposed to zinc (ZnSO\(_4\), 7H\(_2\)O) at four different concentrations: 0 (control treatment), 10, 20 and 40 mg L\(^{-1}\) and cadmium (CdSO\(_4\), 8/3H\(_2\)O) at four concentration of 0 (control treatment), 5, 10 and 20 mg L\(^{-1}\). Each level of cadmium was combined with each level of zinc for a total of 16 treatments (4*4*1) as Cd-0 Zn-0, Cd-0 Zn-10, Cd-0 Zn-20, Cd-0 Zn-40, Cd-5 Zn-0, Cd-5 Zn-10, Cd-5 Zn-20, Cd-5 Zn-40, Cd-10 Zn-0, Cd-10 Zn-10, Cd-10 Zn-20, Cd-10 Zn-40, Cd-20 Zn-0, Cd-20 Zn-10, Cd-20 Zn-20 and Cd-20 Zn-40.

The statistical design was a randomized block of three replicate with 4 plants per each. Plants were received 200 ml of the appropriate solution every day for 3 wk. Every third day the perlite was flushed with deionized water to prevent a potential toxic build up of nutrient salts in the substrate. At harvest, plants were divided into root and shoot fractions. Root tissue samples were rinsed twice in deionized water.
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to remove surface contaminants. Plants samples were air-dried in an oven at 70°C for 48 hours. Dried samples were cut with stainless steel scissors and ground in mortar to obtain homogeneous samples.

2.3. Plant analysis

For calculate plant tolerance index, the dry weight of plant samples was determined. Then tolerance indices (the mean of plant dry weight in each treatment/ mean of plant dry weight in control) × 100 were calculated (Rabie, 2005). For total Cd and Zn analysis, plant samples (0.5 g) were tuned into ash at 550°C in a muffle oven for 8 hours, digested in 3N HNO₃, and analyzed for Cd and Zn using a Shimadzu AA-6200 atomic absorption spectrophotometer.

2.4. Statistical analysis

General Linear Model analyses of variance (ANOVARs) were conducted on the dataset to compare accumulation of zinc and cadmium in shoot and root of M. flavida. For each ANOVA, the normality of the distribution (Kolmogorov-Smirnov) and the homogeneity of variance (Bartlett’s test) were tested. ANOVAs, Tukey HSD test and all statistical analysis were conducted with Statistical software SPSS (version 10).

3. Results

3.1. The effect of different Cd and Zn levels on plant growth

During this 21-day experiment, M. flavida survived in the medium exposed up to 5 mg L⁻¹ Cd, showing no visual Cd toxicity symptoms such as necrosis and whitish-brown chlorosis. The toxicity symptoms became more severe with increasing Cd levels and exposure time. The leaves of M. flavida wilted after the plants were grown for 6 days, and the old leaves began to fall off after growing for 16 days at 20 mg L⁻¹ Cd. Plant biomass and tolerance index were reduced significantly (p<0.05) in both shoot and roots of M. flavida with increasing Cd concentration in nutrient solution (Figs. 1 and 2).

The results indicated that M. flavida growth, measured by plant tolerance and biomass, impacted by Cd treatments at 5-20 mg L⁻¹.

As illustrated in Fig. 1A, the shoot biomass of M. flavida growing in Zn–Cd medium decreased significantly (p<0.01) compared to the control. For example shoot dry weight of M. flavida grown under 10 mg L⁻¹ Cd + 40 mg L⁻¹ Zn, or 20 mg L⁻¹ Cd + 40 mg L⁻¹ Zn was significantly decreased compared to the control, in which Cd-20 + Zn-40 mg L⁻¹ combined treatment decreased the biomass of shoot by 75.2% compared to the control (Fig. 1A). However, shoot biomass in plants exposed to Cd level (5, 10 and 20 mg L⁻¹) was lower in comparison with once affected by Cd + Zn combined treatment. For example shoot biomass of M. flavida exposed to 5 mg L⁻¹ Cd was 19.6 mg while the shoot biomass of plants treated with Cd 5 mg L⁻¹ + Zn 10 mg L⁻¹ was 23.4 mg. The root dry weight of M. flavida under combined concentrations of Zn and Cd in comparison with control is offered in Figure 1B. It is revealed that the dry weight of root were significantly (p<0.05) decreased under the various treatments compared to the control and following the similar pattern of shoot biomass reduction. Maximum (17.6 mg plant⁻¹) and minimum (2.5 mg plant⁻¹) root dry weight were both observed in control (Cd-0 + Zn-0) and Cd-20 + Zn-0 treatments, respectively (Fig.1B).

Tolerance index of M. flavida that expressed as: (dry weight of plant in each treatment/ dry weight of plant in control) × 100 was more sensitive to Cd exposure than Zn treatments. The lowest Cd concentration (5 mg L⁻¹) decreased tolerance index by 45% (P<0.05), whereas 1–10 mg L⁻¹ Zn had no significant effect on its tolerance index. At the highest Cd (Cd-20 + Zn-0) and Zn (Cd-0 + Zn-40) concentration, plant tolerance index was inhibited by 82 and 37.4%, respectively (P<0.01) compared with the control (Cd-0 + Zn-0).

![Fig. 1. Shoot (A) and root (B) dry weight of M. flavida treated with different concentration of Cd (0-20 mg L⁻¹) and Zn (0-40 mg L⁻¹). Bars represent standard error (S.E.) of three replicates](image-url)
Fig. 2. Tolerance index of *M. flavida* treated with different concentration of Cd (0-20 mg L⁻¹) and Zn (0-40 mg L⁻¹).

In this relevance, with the presence of 5 mg L⁻¹ Cd, increasing Zn concentration from 1 to 10 mg L⁻¹ increased tolerance index of *M. flavida* significantly (P<0.05), whereas Cd + Zn combined treatment at Cd-5 + Zn-40 decreased *M. flavida* tolerance index by 52% compared with the control (Fig. 2).

3.2. Cadmium accumulative characteristics of *M. flavida*

The accumulation of Cd in the *M. flavida* shoot was increased with increasing Cd concentrations in the medium when only Cd was present (Fig. 3A). They reached 51, 58 and 124 mg kg⁻¹ in shoot dry weight, at single Cd treatments of 5, 10, and 20 mg L⁻¹ respectively.

The total amount and distribution of Cd accumulated in *M. flavida* under joint stress of Cd and Zn are shown in Fig. 3A. When Zn level was at 40 mg L⁻¹, Cd concentration in the shoots decreased by 27.5%, 45% and 76% at Cd-5, Cd-10 and Cd-40 respectively, compared to (Cd-5+Zn-0). Compared to the low concentration of Zn (10 mg kg⁻¹), the concentration of Cd in the shoots was reduced by 32.6–73.5% at the high level treatment of Zn (40 mg kg⁻¹). The result indicated that the high concentration of Zn had toxic effects on plant Cd uptake (Fig. 3A).

3.3. Zn uptake and partitioning in the *M. flavida* under Cd and Zn treatments

The total amount of Zn and its distribution in *M. flavida* are shown in Figure 3B, the Zn concentration was affected by different cadmium and zinc treatments. It is revealed from Figure 3B that a highest decrease of Zn in *M. flavida* was occurred under combined effect of 20 mg L⁻¹ Cd and 10 mg L⁻¹ Zn.

3.4. Cd and Zn Interactions in the *M. flavida*

Phytotoxicity of *M. flavida* was observed in the 10 and 20 mg L⁻¹ Cd treatments when Zn supply was 0 mg L⁻¹. The symptoms of phytotoxicity were chlorosis symptoms and necrotic spots of leaves. Increasing Zn supply alleviated as phytotoxicity. Shoot and root dry weights were affected significantly by either Cd or Zn treatments (Fig. 1). Cd and Zn accumulation was demonstrated clearly in this experiment, with Cd and Zn concentrations in the shoots reaching up to 124 and 2150 mg kg⁻¹ dry weight, respectively (Figs. 3A and B). Increasing Zn concentration in nutrient solution decreased shoot concentrations of Cd significantly (P < 0.01), in which the effect was proportionally larger in the 40 mg L⁻¹ Zn. For example, in the 10 mg L⁻¹ Cd treatment, increasing Zn from 0 to 40 mg L⁻¹ decreased shoot Cd concentration by 57%. In the 20 mg L⁻¹ Cd treatment, increasing Zn from 0 to 40 mg L⁻¹ decreased shoot Cd concentration by 69%.

The concentrations of Zn in the shoots of *M. flavida* are shown in Fig. 3B. Increasing Cd concentration in the solution decreased the concentration of Zn in the shoots significantly (P< 0.05), independent from the Zn supply level in the medium (10-40 mg L⁻¹). In the treatment with 20 mg L⁻¹ of Cd, Zn concentration in the shoots was 524 mg kg⁻¹, which decreased 4–folds compared to the treatment without Cd addition. Therefore, the interaction effects in *M. flavida* were considered strongly antagonistic with Cd in the presence of Zn.

Fig. 3. Shoot Cd (A) and Zn (B) concentration of *M. flavida* treated with different concentration of Cd (0-20 mg L⁻¹) and Zn (0-40 mg L⁻¹). Bars represent standard error (S.E.) of three replicates
4. Discussion

Cd and Zn are considered to have competition interaction in case of conventional plant species especially in hyperaccumulators (Peris et al., 2007). In the present study, we compared effects of Cd and Zn and the interaction of these heavy metals on M. flavida plants growth, tolerance and these heavy metals accumulation. M. flavida is species from Brassicaceae family which grows naturally around Pb/Zn mining area in Iran with high ability of Zn and Pb accumulation (Ghaderian et al., 2007). Therefore, the study of interaction between a nutrient and a non-essential element may be important for understanding, analyzing and improving the defense strategies through various parameters.

It is revealed that during the time exposure to Cd and Zn, biomass of plant shoots and roots were decreased significantly (P < 0.05) at the threshold concentration of plant growth inhibition under the various Cd and Zn treatments compared to the control. Toxicity symptoms such as chlorosis and necrotic spots were observed in plants grew at 10 mg L\(^{-1}\) and 20 mg L\(^{-1}\) Cd respectively. Positive interactions between Zn and Cd were noted under Cd+ Zn combined treatment in M. flavida. Cadmium toxicity in the shoot was alleviated by Zn treatment, thus these results may approved hypothesis that Zn protects plants from Cd toxicity by competing with Cd in plant cellular metabolism (Sawidis, 2008; Shaw et al., 2004). Similar pattern was also reported in Cd/Zn hyperaccumulator Sodium alfredii (Ye et al., 2003) when exposed to combination of Cd–Zn treatments. Furthermore, de la Rosa et al. (2004) studies on Salsola kali showed that Zn in higher application had protective effects on Cd toxicity up to 20 mg L\(^{-1}\).

Shoots Cd and Zn concentrations increased as substrate Cd and Zn doses increased (Figs. 3A and B). Different plant species and varieties have great variations regarding to the interaction of Cd and Zn (Grant and Bailey, 1997). The inhibitory effect of Cd and Zn on each other was reflected directly by analysis of metal accumulation in M. flavida. Zn supplement (40 mg L\(^{-1}\)) to Cd treated plants (20 mg L\(^{-1}\) Cd) reduced (up to 75%) the accumulation of Zn in comparison with those just treated with 40 mg L\(^{-1}\) Zn. Therefore, Cd decreases Zn uptake and accumulation in M. flavida. Simultaneously the Cd accumulation can be influenced by increasing Zn supply (Adriano, 1986; Nan et al., 2002). Results from the present work showed that Cd toxicity in the shoot of M. flavida was alleviated by Zn treatment, which this was accompanied by a corresponding decrease in shoot concentrations of Cd. Cadmium concentration in shoots decreased significantly with increasing Zn application to the medium (Fig. 3). The presence of Cd also reduced the accumulation of Zn in the roots of Silene vulgaris (Moench) Garke grown hydroponically for only 3 days in concentrations of Cd and Zn that ranged 0–60 μM for Cd and 1–400 μM for Zn (Sharma et al., 1999). In contrast, a combination of 2–5 μM Cd and 10–25 μM Zn in solution culture increased the accumulation of Zn in roots of P. vulgaris L. after 14 days (Chaoui et al., 1997).

The effect of Cd on accumulation and toxicity of Zn is apparently complex and depends on plant species, chemical speciation of Cd, growth medium and the experimental conditions. Due to the strong influences of soil and soil solution chemistry on metal bioavailability, one cannot expect Cd-accumulation under greenhouse or hydroponic conditions to reflect accurately the situation under field conditions. Hewitt (1996) hypothesized that, elements which have similar characteristics in physical and chemical properties act as antagonistic. Zn and Cd have many physical and chemical similarities as they both belong to group II of the periodic table. They are usually found together in the ores and compete with each other for various ligands (Aravind and Prasand, 2005). The fact that Cd is a toxic heavy metal and Zn is an essential element makes this association interesting as it raises the possibility that the toxic effects of Cd may be reducing by Zn (Hart et al., 2002). Cadmium acts as a Zn analogue and is transported across the plasma membrane via a Zn transport systems (Hart et al., 2006; Ullrich-Erebian et al., 1989). Once inside the cytoplasm Cd competes with Zn, for example replacing Zn in reactive enzymatic and receptor proteins which lead to inactivate their functions (Das et al., 1997, Sawidis, 2008; Shaw et al., 2004). These results support the observations that the nutritional status of the plant will affect the processes involved in metal uptake and translocation.

The effect of Zn on the accumulation of Cd depended on the dose provided. When Cd and Zn were present together in low concentrations, 40–47% lower concentrations of Cd were measured in shoots as compared to the concentrations found in tissues from plants grown with Cd only (Fig. 2a). Others have reported that addition of Zn to hydroponic culture decreased Cd-accumulation (Hart et al., 2005; Lombi et al., 2001; McKenna et al., 1993). In Zn-deficient soil (Oliver et al., 1994) and soil with 0.145 mg kg\(^{-1}\) Cd (Choudhary et al., 1995), addition of Zn (up to 20 mg/ha and 30 mg kg\(^{-1}\), respectively) also reduced the uptake of Cd in mature plants. This means that the ability of metal uptake by the plants not only rests upon the concentrations of heavy metals but also relates to their combinations (Zhou, 1995). Not only can Zn affect the uptake and translocation of Cd, but it appears to vary in effect depending on the relative amounts of Cd and Zn present in the soil. In particular, the Zn-status of the plant may be very important. The addition of Cd to a Zn-deficient soil may result in further accumulation of Cd in the plant, in part due to the higher affinity of the Cd/Zn transporter for Cd (Hart et al., 2002). In contrast, adequate Zn-nutrition may help protect the plant from Cd-toxicity (Köleli et al., 2004) and more
Cd may be immobilized in the root tissues. Either Zn- or Cd-toxicity will cause impaired physiological functions, which may result in uncontrolled uptake of toxic metals. As with the effect of Cd on accumulation of Zn, the effect of Zn on accumulation of Cd is apparently complex and differs from relative metal concentration. As discussed above, the nutritional status of the plant will affect the processes involved in metal uptake and translocation.

The plant, *M. flavida,* accumulated a maximum of 124 mg Cd kg⁻¹ dry mass in shoots when cultivated for 21 days in hydroponic medium. The tolerance of *M. flavida* to Cd and Zn is greater than that observed for many nonaccumulating plant species, which have a threshold concentration for phytotoxicity between 5 and 100 mg kg⁻¹ dry weight (Solís-Dominguez et al., 2007).

Generally, Cd and Zn accumulation were determined by their concentration in plant tissue and biomass production. Increased of the Cd and Zn concentration in this study could be explained by two sides. On the one hand, the *M. flavida* growth as morphological characters and biomass production was nearly unaffected by the increase of Cd and Zn concentration in medium and there were few visible symptoms of withered leaves and chlorosis (Fig. 1). On the other hand, the Cd and Zn concentrations in *M. flavida* tissue were significantly increased with increasing Cd and Zn levels in the nutrient solution (Fig. 3).

Cadmium tolerance in higher plants should in general be defined as the natural or artificially given capacity, regulated by interacting genetic and environmental factors, to bear high levels of Cd exposure for a long time, without appreciable detrimental effects on metabolism (Ghosh and Singh, 2005). Thus, the development of ‘real’ Cd tolerance should be a long-term process (possibly years) and involve modifications in the genetic patrimony of the plant. Therefore, an ideal plant for phytoextraction application should have high metal tolerance and high accumulation capacity in its tissues (especially in harvestable parts) (Shi and Cai, 2009). Furthermore, the biomass production of the plant, which limited the actual phytoextraction application in contaminated field is an important factor for determining tolerant plants.

The phytoremediation efficiency is determined by the amount of metal transported to the aboveground tissues, and the aboveground biomass of the hyperaccumulating plant. The results presented here show that *M. flavida* is fast growing plant and it could extract relatively large amount of Zn or Cd in their aboveground part in comparison with plants growing on Cd or Zn contaminated area (*Sorghum sp; Iris sp, Atriplex halimus, Echinocloa polystachya* and some populations of *Sedum alfredii*), which shows it possibly used for phytoremediation of Cd or Zn contaminated area (Deng et al., 2007; Han et al., 2007; Nedjimi and Daoud, 2009; di Toppi et al., 1999).

Fast-growing plant as the examined *M. flavida* exhibited higher phytoextraction efficiency with higher biomass production but relative lower cadmium concentration in comparison with some species of hyperaccumulator plants (Figs. 1-3). The results at least partly demonstrated the hypothesis that fast-growing plant had the higherremedying efficiency compared with the other slow-growing hyperaccumulators.

5. Conclusions

The results indicated that *M. flavida* had the relative tolerance to high levels of Cd and Zn which it tolerate up to 20 and 40 mg L⁻¹ Cd and Zn respectively.

Interactions between Zn and Cd led to a decrease in Zn and Cd uptake when the metals co-occurred in high concentrations, likely due to the competition between Cd and Zn. The ability of *M. flavida* to withstand the high concentrations of Cd and Zn, high tolerance ability and short growing cycle suggests that this plant has a mechanism to detoxify the Cd and Zn. This could make it possible because of its higher robustness and Cd accumulation capacity, potential candidates for phytoremediation purposes in Iran, and in addition to that, because they are adapted to the local climate and soil conditions.

This study provides a promising start for biomass-based phytostabilization and phytoextraction; it includes high biomass production species, and growing these species is practically easier than the production of hyperaccumulators. Therefore, *M. flavida* can be indicated as a remediant in soil contaminated with Zn and Cd.

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References


