Environmental Science and Pollution Research (2018) 25:12507–12514
https://doi.org/10.1007/s11356-018-1486-4

RESEARCH ARTICLE

Comparisons of cadmium bioaccumulation potentials and resistance physiology of *Microsorum pteropus* and *Echinodorus grisebachii*

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Received: 29 November 2017 / Accepted: 4 February 2018 / Published online: 20 February 2018

Abstract

To better monitor and remediate environments contaminated by cadmium (Cd), plants are used as hyperaccumulators or biomonitors; however, few have been identified for aquatic Cd pollution. In our study, two aquatic ornamental plants, *Microsorum pteropus* (Blume) Copel. and *Echinodorus grisebachii* Small, were studied for their Cd accumulation capacity, morphological characteristics, and leaf physiological indexes. *Microsorum pteropus* (Blume) Copel. leaf has the potential to hyperaccumulate Cd (166 mg/kg dry weight for 1 mg/L exposure), with no significant physiological difference under exposure. *Echinodorus grisebachii* Small had sensitive diagnostic responses to Cd toxicity, such as significant decreases in Chl (a + b) and Chl-a/b, increased peroxidase (POD) activity, greater malondialdehyde (MDA) content, and increased soluble sugar content. These results suggest that *Microsorum pteropus* (Blume) Copel. could have the potential to be a Cd hyperaccumulator, while *Echinodorus grisebachii* Small could serve as a biomonitor for Cd-contaminated water bodies.

Keywords Cadmium · *Microsorum pteropus* · *Echinodorus grisebachii* · Bioaccumulation · Resistance physiology

Introduction

Cd pollution has become a worldwide environmental problem since the "bone-pain illness" that occurred during the 1950s–1970s (Wang et al. 2005). Long-term intake of Cd-contaminated food and drinking water causes toxic effects on the human lung, kidney, skeletal system, and respiratory system (IARC 1993; WHO 2010). In 1993, Cd and its compounds were classified as group 1 carcinogenic compounds to humans (IARC 1993).

Phytoremediation is an in situ treatment strategy known for its cost effectiveness, easy maintenance, minimal waste generation, and ability to remove low-level heavy metal contamination (ITRC 2010) in polluted soil or water (Salt et al. 1995). Phytoremediation depends heavily on the screening of hyperaccumulators, which could rapidly and effectively uptake heavy metals and sequester them in the aerial part of the plant (Baker et al. 1983; Brooks et al. 1977; Rascio and Navari-Izzo 2011). For the 20 some identified Cd hyperaccumulators (Baker et al. 1994; Bert et al. 2003; Li et al. 2007; Liu et al. 2004; Nie 2006; Speiser et al. 1992; Su and Huang 2001; Wei and Zhou 2006; Wei et al. 2005; Yang et al. 2004), *Brassica juncea* (L.) Czern. (Speiser et al. 1992) was the first discovered Cd hyperaccumulator, *Thlaspi caerulescens* J.Presl & C.Presl (Baker et al. 1994) has the highest Cd accumulation concentration (2130 mg/kg), and *Scirpus tabernaemontani* C.C.Gmel. (Li et al. 2007) is the only aquatic plant.

Plant biomonitoring is a widely used strategy to evaluate pollutant contamination in the environment, which takes advantage of the quantitative characteristics of the plant indicators or biomonitors under pollutant exposure (Gorelova and Frontasyeva 2017; Zhou et al. 2008). Algae (Torres et al. 2008), macrophytes (Bonanno 2013; Kumar et al. 2006) and seagrasses (Bonanno and Di Martino 2016) are frequently applied for aquatic environment biomonitoring (Zhou et al. 2008), while lichens and mosses (Peng and Lu 2008) are used for air biomonitoring. For the freshwater system, macrophytes are usually longer living, more widespread, and easily identified (Gorelova and Frontasyeva 2017; Zhou et al. 2008), making it appropriate for large-scale sampling and detection. Aquatic macrophytes like *Myriophyllum spicatum* L.

Responsible editor: Elena Maestri

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(Yabanli et al. 2014), *Pistia stratiotes* L. (Das et al. 2014) and *Nasturtium officinale* R. Br. (Gounden et al. 2016) has been observed for their heavy metal accumulation capacity, which could be used as bioindicators in waters.

To identify biomonitors and hyperaccumulators, it is essential to study their morphological and physiological changes under heavy metal stress. Biomonitors would have "clearly marked and reproducible" diagnosis effects (Gorelova and Frontasyeva 2017) sensitive to low levels of contaminated environment. Meanwhile, hyperaccumulators would have a great detoxification capacity, with no significant physiological changes under high-level exposure (Rascio and Navari-Izzo 2011). Cd toxicity would cause plant growth retardation, leaf withering, and leaf chlorosis (Basa et al. 2014; Ederli et al. 2004), which is related to the decrease of chlorophyll content (Kučera et al. 2008; Mishra et al. 2006). The Chl content reduction is related to Cd-induced Fe deficiency (Basa et al. 2014) or to Cd interference with SH sites, which reduce the activity of ALA dehydratase and protochlorophyllide reductase and lead to Chl synthesis inhibition (Kučera et al. 2008; Mishra et al. 2006). Oxidative stress, as a secondary effect by Cd toxicity (Basa et al. 2014; Kučera et al. 2008), could be described by the accumulation of malondialdehyde (MDA) content, the increasing antioxidant enzyme activity (Alscher and Hess 1993; Rascio and Navari-Izzo 2011) and the increasing antioxidant molecule content (van de Mortel et al. 2008). Cd stress induces excessive production of oxygen free radicals, causing membrane lipid peroxidation and accumulation of its product (malondialdehyde, MDA), which further leads to irreversible organelle damage, cytomembrane structure modification, DNA damage, etc. (Aravind and Prasad 2003; Kučera et al. 2008; Tang et al. 2006). Antioxidant systems could effectively counteract oxidative stress (Alscher and Hess 1993; Chiang et al. 2006; Rascio and Navari-Izzo 2011), with non-enzymatic antioxidant molecules such as glutathione (GSH) (van de Mortel et al. 2008) and ascorbic acid (AsA) (Küpper et al. 1999) and antioxidant enzymes such as superoxide dismutase (SOD), peroxidation (POD), catalase (CAT), and glutathione reductase (GR). In terms of material metabolism, Cd toxicity could lead to essential metabolite content changes (e.g., amino acids, proteins, and sugars), as a potential detoxification mechanism in plants. Cd could cause soluble protein content reduction (Singh et al. 2006) and increases in soluble sugar content (Guo et al. 2007; Wang et al. 1984).

In our study, two aquatic ornamental plants, *Microsorum pteropus* (Blume) Copel. and *Echinodorus grisebachii* Small were selected as the experimental plants. *Microsorum pteropus* is a species in the Polypodiaceae family in Pteridopsida, while *Echinodorus grisebachii* is a monocotyledon species in the Alismataceae family. Both species can grow in fully or partially submerged environments and are frequently used in aquariums. For both plants, the Cd accumulation capacity, morphological characteristics, and leaf physiological indexes (including chlorophyll content, the degree of oxidative damage and metabolite content) were measured to evaluate and compare their potential to accumulate and detoxify Cd, which would further tell us the possibility of using *Microsorum pteropus* and *Echinodorus grisebachii* as hyperaccumulators or biomonitors.

Materials and methods

Plant materials and Cd exposure

Microsorum pteropus and *Echinodorus grisebachii* samples were selected and purchased at the Da Sen Lin flower market, Beijing. All plants were fully submerged in 10% Hoagland solution for 1 week cultivation (temperature, 17.5 °C ± 0.5 °C; light, natural light). After that, plants with similar size and growth status were selected and exposed to 0, 0.1, 1, 5, 10, or 20 mg/L Cd^{2+} in 10% Hoagland solution (pH, 6.0 ± 0.3) by adding $CdCl_2$. Considering the relative high cadmium pollution in waters, the highest Cd exposure concentration was expanded from 3 to 5 mg/L in former studies (Saygideğer 2000; Wang et al. 2008) to 20 mg/L in our study. Three replicates were set for each exposure group. After 7 days of exposure, all plant samples were washed with tap water and deionized water, dried by absorbent paper, and stored at − 20 °C.

Cd content measurement

Leaves were dried in an FDU-830 freeze-dryer for 24 h, preheated at 150 °C in a 50-mL porcelain crucible for 1 h, and carbonized in a muffle furnace for 4–5 h (heated from 200 to 550 °C, staying at 200, 300, 400, 500 °C for 0.5 h each). After cooling, ashes were digested in 5 mL 10% nitric acid at 150 °C, with total volume reduced to approximately 0.5 mL, diluted to 25 mL with 1% nitric acid, and measured on an atomic absorption spectrophotometer (HITACHI180-80). Standard $Cd(NO_3)_2$ solution was added to blank *Microsorum pteropus* leaf as certified reference material. The bioconcentration factor (BCF) is calculated using the equation as below (Arnot and Gobas 2006).

$$\mathrm{BCF} = \frac{C_B(\text{chemical concentration in the organism})}{C_{WD}(\text{chemical concentration in the water})}$$

Physiological indicator measurement

The fresh leaf samples of *Microsorum pteropus* and *Echinodorus grisebachii* were cut into 1-mm-wide pieces without veins to further determine physiological indicators including chlorophyll content, malonaldehyde (MDA) content, soluble sugar, superoxide dismutase (SOD) activity, peroxidase (POD) activity, and soluble protein content.

For chlorophyll content, 0.2 g of leaf was weighed and digested in 10 mL acetone/ethanol [2: 1 (*v*: *v*)] for 48 h in the dark. Extracts were diluted to 25 mL and measured on a UV spectrophotometer for its absorbance at 645 and 663 nm. Arnon's equation (Arnon 1949) was used for quantification of the chlorophyll a and chlorophyll b content.

$$\text{Chlorophyll a } (\mu g/ml) = 12.7\ (A_{663}) - 2.69\ (A_{645})$$
$$\text{Chlorophyll b } (\mu g/ml) = 22.9\ (A_{645}) - 4.68\ (A_{663})$$

The MDA content and soluble sugar content were measured by the TBA method (Zhao et al. 1994). 0.5 g of leaf was weighed and ground to homogenate in 1 mL 10% TCA (trichloroacetic acid) with a small amount of quartz sand. After that, another 4 mL 10% TCA was added for further grinding. The homogenate was centrifuged at 400 rpm for 10 min. Two milliliters supernatant was extracted, mixed with 2 mL 0.6% TBA (thiobarbituric acid, diluted with 10% TCA), and heated in boiling water bath for 15 min. After rapid cooling and centrifugation, absorbance of the supernatant was measured at 532, 600, and 450 nm by a microplate reader (Model 680).

For SOD activity, POD activity, and soluble protein content, 0.2 g of leaf was ground with 1 mL precooled phosphate buffer (0.05 mol/L, pH = 7.8 for SOD; 1 mol/L, pH = 7.0 for POD and soluble protein) in a mortar kept in ice bath, then transferred to a centrifuge tube with 4 mL buffer and centrifuged at 4500 rpm for 20 min. The supernatant was used for further analysis.

SOD activity was measured by the photochemical NBT method (Durak et al. 1993). 0.05 mL supernatant was mixed with 1.5 mL 0.05 mol/L phosphate buffer, 0.3 mL 130 mmol/L met solution, 0.3 mL 750 μmol/L NBT solution, 0.3 mL 100 μmol/L EDTA-Na_2, 0.3 mL 20 μmol/L riboflavin, and 0.25 mL deionized water in a 5-mL tube. Phosphate buffer instead of supernatant was added into two control tubes. All tubes were placed under 4000 lx daylight for 20 min, except one control tube was placed in the dark as a blank. The absorbance at 560 nm was read by a microplate reader (Model 680). One SOD activity unit is defined as one enzyme activity unit that inhibits 50% of the NBT photochemical reduction.

For POD activity, 60 μL supernatant was mixed with 120 μL 0.1 mol/L phosphate buffer, and 60 μL 20 mmol/L H_2O_2. After 60 μL 20 mmol/L pyrogallol was added, a microplate reader (Model 680) was used to measure the changes in absorbance per minute at 450 nm. POD activity is defined as the amount of enzyme required for a 0.01 absorbance change at 25 °C for 1 min under standard conditions.

The soluble protein content was measured by the Bradford method (Bradford 1976; Li 2000). 0.1 mL of supernatant was mixed with 5 mL Coomassie bright blue, with the absorbance measured at 595 nm and calculated based on a calibration curve, using bovine serum albumin (BSA) as the standard protein.

Statistical analysis

The results are presented as the mean ± standard deviations (SD), with three replicates measured for each exposure condition. LSD tests were conducted in SPSS 13.0 to analyze the significant differences between groups.

Results

Cd accumulation ability

The concentration and bioconcentration factor (BCF) of Cd in *Microsorum pteropus* and *Echinodorus grisebachii* leaves are shown in Table 1. For both plants, Cd concentration in leaves rose with increasing exposure concentration. For a 1 mg/L Cd exposure concentration, the accumulation concentration in *Microsorum pteropus* reached 166 mg/kg dry weight (DW), which is higher than the standard of Cd hyperaccumulator (100 mg/kg, Baker et al. 1983). Meanwhile, the Cd concentration in *Echinodorus grisebachii* leaf was only 14.55 ± 5.13 mg/kg DW. In the range of 0.1–20 mg/L Cd exposure, the BCFs of *Microsorum pteropus* were within 123.37–224.41, which is much higher than the BCFs of *Echinodorus grisebachii* (11.1–31.1). These suggest that the

Table 1 The Cd accumulation concentration and bioconcentration coefficient (BCF) in *Microsorum pteropus* and *Echinodorus grisebachii* leaves

Initial Cd concentration (mg/L)	*Echinodorus grisebachii*		*Microsorum pteropus*	
	Cd conc. (mg/kg)	BCF (L/kg)	Cd conc. (mg/kg)	BCF(L/kg)
0 (control)	0.21 ± 0.09		1.64 ± 0.68	
0.1	2.22 ± 0.71	31.1	22.44 ± 8.07	224.41
1	14.55 ± 5.13	18.9	166.08 ± 65.01	166.08
5	54.92 ± 15.68	13.1	627.99 ± 298.45	125.6
10	116.53 ± 25.77	14.7	1233.75 ± 587.38	123.37
20	169.71 ± 52.35	11.1	2574.94 ± 957.66	128.75

Microsorum pteropus leaf has the ability to accumulate Cd, whereas *Echinodorus grisebachii* does not.

Apparent growth

Growth retardation, leaf withering, and leaf chlorosis are obvious symptoms of plants under Cd stress (Ederli et al. 2004). Although a few dark spots were observed on several leaves after 10 and 20 mg/L exposure, the apparent growth of *Microsorum pteropus* was basically the same after 7 days of exposure, with no leaves rotten or defected. Meanwhile, *Echinodorus grisebachii* leaves were significantly discolored and withered compared with the control group, with increasing leaf damage occurring under rising exposure concentrations. At a 20 mg/L Cd exposure, the concentration of *Microsorum pteropus* and *Echinodorus grisebachii* leaves were 2574.9 4 ± 957.66 mg/kg and 169.71 ± 52.35 mg/kg DW, respectively, and all the leaves of *Echinodorus grisebachii* were significantly withered and discolored.

Chlorophyll content

The total chlorophyll content and Chl-a/Chl-b ratio of both plants are depicted in Fig. 1. For *Echinodorus grisebachii*, a significant negative correlation ($p < 0.01$) was found between exposure concentration and Chl (a + b) ($r = -0.997$) and Chl-a/Chl-b ($r = -0.989$). Compared with the control group (1.56 mg/g), the Chl (a + b) concentration, and Chl-a/Chl-b ratio under 10 mg/L ($p_1 < 0.01$, $p_2 < 0.05$) and 20 mg/L ($p_1 = 0.001$, $p_2 < 0.001$) exposure decreased significantly.

For *Microsorum pteropus* leaves, no significant difference ($p > 0.05$) was observed between the Chl (a + b) content ($p > 0.05$) and Chl-a/Chl-b ratio ($p > 0.05$) of treatment groups and control group (1.63 mg/g), except for the Chl (a + b) concentration at 10 mg/L exposure (1.24 mg/g, $p < 0.05$). The results indicate that *Echinodorus grisebachii* leaf was significantly affected by Cd, while *Microsorum pteropus* was not.

MDA content

Except for the 20 mg/L exposure group, a significant positive correlation was observed between MDA content and Cd concentration ($p < 0.01$, $r = 0.974$) of *Echinodorus grisebachii*. MDA content significantly increased at 1, 5, and 10 mg/L Cd exposure ($p < 0.05$, Fig. 2), indicating the increasing membrane lipid peroxidation caused by excess free radicals, as a large amount of oxygen free radicals are induced by Cd stress and could not be completely removed by the rising antioxidant enzyme activity (see "The activity of SOD and POD"). The membrane lipid peroxidation caused the accumulation of MDA and soluble sugar, resulting in leaf withering and chlorosis. The MDA content of the 20 mg/L exposure group (0.298 mmol/L) was significantly lower than that of the 10 mg/L exposure group (0.858 mmol/L), which may be caused by cell rupture of leaf tissue.

For the MDA of *Microsorum pteropus* leaf, no significant difference ($p > 0.05$) was found between treatment group and control group (Fig. 2).

The activity of SOD and POD

Compared with the control group, the SOD activity of *Echinodorus grisebachii* was higher under Cd stress (Fig. 3). For the SOD activity of both plants (Fig. 3), no significant difference ($p > 0.05$) was found between control group and treatment group, except for the 1 mg/L exposure group of *Microsorum pteropus* ($p < 0.05$) which may represent special tolerance mechanisms under Cd stress.

Figure 4 depicts the POD activity of both plants under different Cd concentrations. For *Echinodorus grisebachii*, a significant positive correlation ($p < 0.01$, $r = 0.918$) was found between the POD activity and Cd exposure concentration. Except for the 1 mg/L exposure group, the POD activities of all treatment groups were higher than that of the control group, while the POD activity at 20 mg/L exposure was 0.71 times more than that of the control group. The results above indicate oxidative damage under Cd stress, resulting in a large amount

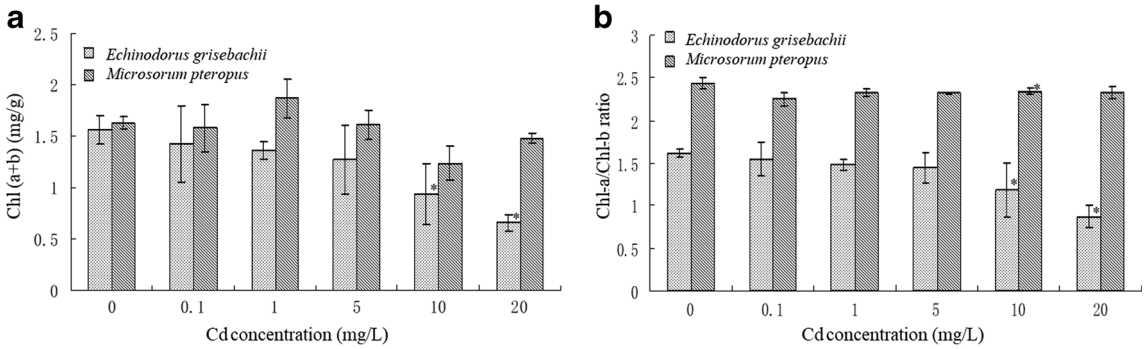

Fig. 1 The Chl(a + b) (**a**) and Chl-a/Chl-b (**b**) of *Echinodorus grisebachii* and *Microsorum pteropus* under Cd exposure (*$p < 0.05$)

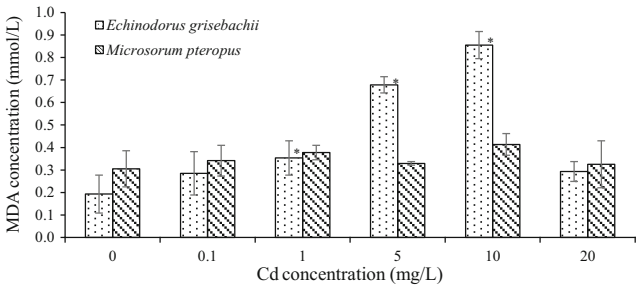

Fig. 2 The MDA content of *Echinodorus grisebachii* and *Microsorum pteropus* under Cd exposure (*$p < 0.05$)

of oxygen free radicals, which induced POD activity enhancement. Meanwhile, for *Microsorum pteropus*, no significant difference ($p > 0.05$) was found between the control group and treatment groups.

Soluble protein and sugar content

For the soluble protein content of both plants, no significant difference ($p > 0.05$) was found between treatment groups and control group (Fig. 5). The soluble protein content of *Echinodorus grisebachii* was highest at 1 mg/L exposure (1.5 times the control) and lowest at 5 mg/L Cd stress (58.96% of the control).

For *Echinodorus grisebachii* leaf, the soluble sugar content (Fig. 6) was significantly positively correlated with the Cd exposure concentration ($p < 0.01$, $r = 0.969$). Compared with the control group, the soluble sugar content of *Echinodorus grisebachii* leaf at 10 mg/L ($p < 0.05$) and 20 mg/L ($p = 0.001$) exposure was significantly increased. Meanwhile, no significant difference ($p > 0.05$) was found between treatment group and control group for the soluble sugar content of *Microsorum pteropus* leaf (Fig. 6).

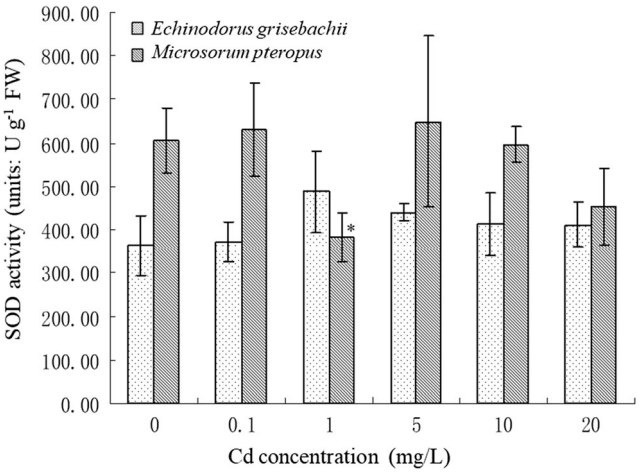

Fig. 3 The SOD activity of *Echinodorus grisebachii* and *Microsorum pteropus* under Cd exposure (*$p < 0.05$)

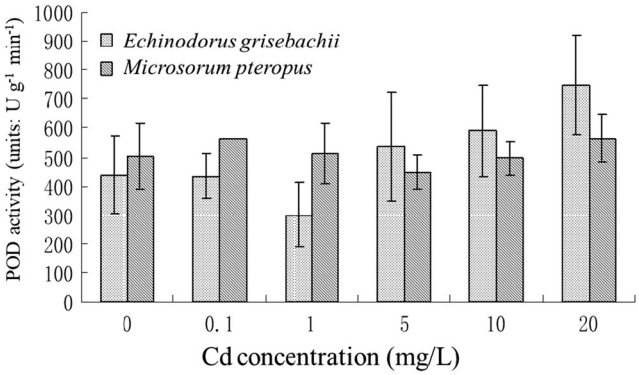

Fig. 4 The POD activity of *Echinodorus grisebachii* and *Microsorum pteropus* under Cd exposure

Discussion

The above results indicate that *Microsorum pteropus* has the potential to hyperaccumulate Cd. The BCFs (123.37-224.41) of *Microsorum pteropus* leaf remained at relative high level with rising exposure concentration, while the leaf Cd concentration (166 mg/kg DW, under 1 mg/L exposure) was much higher than the standard of Cd hyperaccumulator (Baker et al. 1983). Meanwhile, the leaf physiological indexes (including chlorophyll content, MDA content, soluble sugar content, SOD activity, POD activity, and soluble protein content) did not change significantly with increasing cadmium exposure concentration, indicating its self-repairing mechanism against Cd toxicity. Therefore, *Microsorum pteropus* has the potential to hyperaccumulate Cd, which was confirmed in our further study of *Microsorum pteropus* under high Cd exposure (20, 40, 60, 80, 100 mg/L) (Lan et al. 2018). By contrast, most leaf physiological indexes of *Echinodorus grisebachii* (including chlorophyll content, MDA content, soluble sugar content, and POD activity) changed significantly under Cd stress with a much lower Cd accumulation concentration in leaf (about 1/10 that of *Microsorum pteropus*). However, comparing to other aquatic macrophytes, the cadmium concentration of *Echinodorus grisebachii* is relatively high (about 1000 times higher than *Pistia stratiotes* (Das et al. 2014) under 1 mg/L Cd

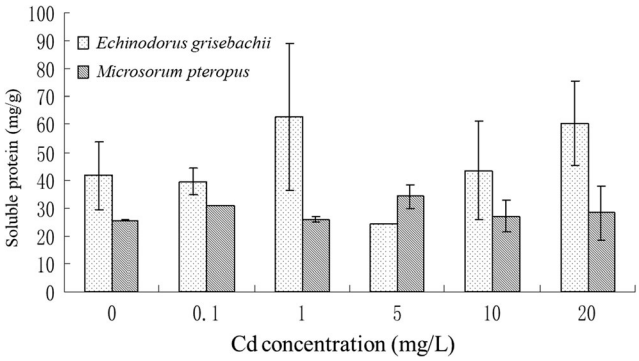

Fig. 5 The soluble protein content of *Echinodorus grisebachii* and *Microsorum pteropus* under Cd exposure

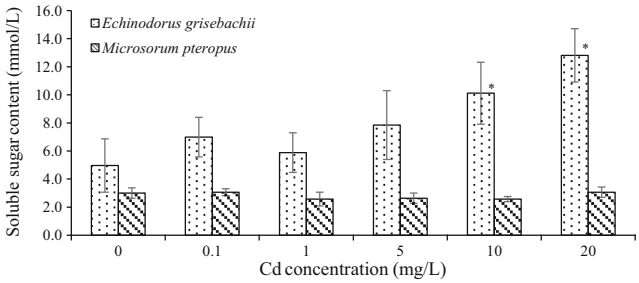

Fig. 6 The soluble sugar content of *Echinodorus grisebachii* and *Microsorum pteropus* under Cd stress (*$p < 0.05$)

exposure, as an example), making *Echinodorus grisebachii* a sensitive indicator.

Cd stress will inhibit the synthesis of chlorophyll (Chl) and interfere with PSII function (Basa et al. 2014), with leaf discoloration being the apparent photosynthetic damage characteristic. As a basic indicator of plant damage, the chlorophyll (Chl) content was not significantly changed under Cd stress ($p > 0.05$) for *Microsorum pteropus* leaf, which suggests a potential self-repair mechanism in photosynthesis. Meanwhile, significant toxic effects could be observed for *Echinodorus grisebachii* leaf. The Chl content was significantly decreased under Cd stress, with Chl-a decreasing remarkably more than Chl-b, which is similar to the study of *Jussiaea repens* (Li et al. 2008).

Cd stress will induce the generation of excessive reactive oxygen free radicals, followed by free radical metabolic imbalance with a decreasing free radical scavenging enzyme activity, which further causes membrane lipid peroxidation (Kučera et al. 2008; Luo et al. 1998; Tang et al. 2006). As the product of intracellular membrane lipid peroxidation or degreasing, malondialdehyde (MDA) would reduce the unsaturated fatty acid content in membrane and lower the membrane fluidity. Therefore, a higher MDA content indicates a higher degree of membrane lipid peroxidation in plants (Guo et al. 2007), and a lower ability to scavenge free radicals (Luo et al. 1998). Under Cd stress, no significant effect was found for the MDA content of *Microsorum pteropus* compared with the control group, while the MDA content ($p < 0.01$, except for the 20 mg/L exposure group) of *Echinodorus grisebachii* increased significantly, indicating a serious molecular damage to plant cells.

The antioxidant enzyme system is usually induced to eliminate excessive oxygen free radicals, with increasing activities of superoxide dismutase (SOD), peroxidase (POD), etc. SOD converts oxygen free radicals into H_2O_2 and O_2, while POD decomposes H_2O_2 by catalyzing the oxidation of phenolic compounds or antioxidants. Therefore, the activities of SOD and POD reflect the Cd accumulation and the degree of oxidative damage in plants (Zhang et al. 2007). In our study for *Echinodorus grisebachii*, the SOD activity increased under Cd stress with no significant difference ($p > 0.05$) and the POD activity was positively correlated with the exposure concentration ($p < 0.01$, $r = 0.918$), while the accumulation of MDA indicated the excess free radicals could not be completely removed by the rising antioxidant enzyme activity. For the SOD and POD activity of *Microsorum pteropus*, no significant difference ($p > 0.05$) was found between the control group and treatment group, except for the SOD activity for 1 mg/L exposure group ($p < 0.05$). The results of MDA, SOD, and POD indicate that *Echinodorus grisebachii* leaf cell was seriously damaged under Cd stress, while *Microsorum pteropus* was not.

As an indicator for maintaining osmotic balance under stress, the soluble protein content in plants is seen as the degree of oxidative stress in plants (Hou et al. 2007; Singh et al. 2006). Although the mechanism of Cd exposure on soluble protein content is unclear, various studies have revealed its role in plant resistance under stress. Sun et al. (2009) have found the leaf soluble protein content decreases with increasing Cd exposure; Guo et al. (2007) have found the leaf soluble protein content is significantly lower for Cd-sensitive rice genotypes under Cd stress, with no effect on resistant species. Lagriffoul et al. (1998) have found the soluble protein content increases under Cd exposure in *Zea mays* L. leaves. In our study, no significant difference ($p > 0.05$) was found between the treatment groups and control group for both plants, indicating osmotic adjustment is not a major anti-stress mechanism for both plants.

The soluble sugar content in plants can reflect the synthesis of carbohydrates (Liu et al. 2005). For *Microsorum pteropus*, no significant difference is found for the soluble sugar content under Cd stress compared with the control group. Meanwhile, sugar accumulation induced by Cd stress (Guo et al. 2007) could be observed for *Echinodorus grisebachii* leaf, with soluble sugar content significantly positively correlated with the Cd exposure concentration ($p < 0.01$, $r = 0.969$).

Conclusions

(1) *Microsorum pteropus* leaf has a higher Cd accumulation concentration (166 mg/kg DW, under 1 mg/L exposure) than the standard of Cd hyperaccumulator (100 mg/kg, Baker et al. 1983), with no significant changes occurring under exposure for several leaf physiological indexes, including chlorophyll content, MDA content, SOD activity, POD activity, soluble protein content, and soluble sugar content.

(2) *Echinodorus grisebachii* is significantly oxidative damaged under Cd exposure. For *Echinodorus grisebachii* leaf, Chl (a + b) and Chl-a/b is significantly decreased, while the POD activity, MDA content (except 20 mg/L group), and soluble sugar content have a significantly positive correlation with Cd exposure concentration.

(3) *Microsorum pteropus* has the potential to hyperaccumulate Cd and could be applied to remediate Cd-contaminated water bodies. Meanwhile, *Echinodorus grisebachii* has a below-standard accumulation ability and significant damage characteristics, making it sensitive to Cd, and could be applied as a biomonitor for Cd-contaminated water bodies.

(4) For both plants, the chlorophyll content, POD activity, MDA content, and soluble sugar content are sensitive indexes of Cd stress, while SOD activity and soluble protein content are insensitive.

Funding information The funding for this study was provided by the National Science Foundation of China (NSFC) (31570508). This work is also supported by the Undergraduate Student Research Training Program of the Ministry of Education.

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