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Heavy Metal Phytoremediation by Water Hyacinth at Constructed Wetlands in Taiwan

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ABSTRACT

The ability of water hyacinth (*Eichhornia crassipes* Mart. Solms.) to absorb and translocate cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), and nickel (Ni) was studied in the Erh-Chung wetlands. Translocation ability was defined as the quantity of Cu, Pb, Cd, Ni, and Zn translocated in the plant's tissues, and was expressed as a root/shoot ratio. The ratio results were in the order of Cu>Pb>Cd>Ni>Zn. Water hyacinth plants had a high bioconcentration of these trace elements when grown in water environments with low concentrations of the five elements. Generally, the concentration of these five elements in the roots was 3 to15 times higher than those in the shoots. The concentrations in the root tissue were found in the order of Cu>Zn>Ni>Pb>Cd. The absorption capacity for water hyacinth was estimated at 0.24 kg/ha for Cd, 5.42 kg/ha for Pb, 21.62 kg/ha for Cu, 26.17 kg/ha for Zn, and 13.46 kg/ha for Ni. This study shows water hyacinth to be a promising candidate for phytoremediation of wastewater polluted with Cu, Pb, Zn, and Cd.

Key words: Bioaccumulation, bioconcentration factor, translocation ability, absorption capacity.

INTRODUCTION

Developing cost effective and environmentally friendly technologies for the remediation of soils and wastewaters polluted with toxic substances is a topic of global interest. The value of metal-accumulating plants to wetland remediation has been recently realized (Black 1995). This capability is useful in removing toxic heavy metals and trace elements from contaminated soils and waters in a process referred to as phytoremediation. Several terrestrial plants that have been identified in the last two decades as highly effective in absorbing and accumulating various toxic trace elements are being evaluated for their role in the phytoremediation of soils polluted with trace elements (Baker et al. 1994, Tang et al. 2001). Raskin et al. (1994) defined rhizofiltration as the use of plant roots to absorb heavy metals from polluted effluents. Duckweed (*Lemna minor* L.) and water velvet (*Azolla pinnata* R. Br) have been shown to bioconcentrate metals such as Fe and Cu by up to 78 times the concentrations in the wastewater (Jain et al. 1989). Pinto et al. (1987) demonstrated that water hyacinth would remove silver from industrial wastewater for subsequent recovery with high efficiency in a fairly short time. The accumulation of some other heavy metals and trace elements in many species of wetland plants has also been demonstrated (Dunbabin and Bowmer 1992, Delgado et al. 1993, Fett et al. 1994, Salt et al. 1995, Zaranyika and Ndapwadza 1995, Zayed et al. 1998, Zhu et al. 1999). Water hyacinth has been used successfully in wastewater treatment systems to improve the quality of water by reducing the levels of organic and inorganic nutrients (Brix 1993, Delgado et al. 1995) and readily reducing the level of heavy metals in acid-mine drainage water (Falbo and Weaks 1990). Furthermore, the quantity of trace elements that can be accumulated by water hyacinth has been shown to correlate well with concentration of heavy metals in the water (Ismail et al. 1996).

Trace element removal by wetland vegetation can be greatly enhanced by selection of appropriate wetland plant species. The selection is based on the types of elements to be remediated, the geographic location, microclimate, hydro-

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logic conditions, soil properties, and known accumulation capacities of the species. Knowledge of the capabilities of different wetland plant species to absorb and transport trace elements under different conditions is important to know. One such plant is the vascular aquatic plant water hyacinth which is commonly found in tropical and subtropical regions of the world. Water hyacinth is a fast growing, floating plant with a well developed fibrous root system and large biomass. It adapts easily to various aquatic conditions and plays an important role in extracting and accumulating metals from water. Hence, water hyacinth is considered to be an ideal candidate for use in the rhizofiltration of toxic trace elements from a variety of water bodies. This study aims to determine the suitability of this plant for phytoextracting toxic heavy metals (Cd, Cu, Ni, Pb, and Zn) commonly found in industrial wastewater, domestic wastewater, and seepage water from illegal landfills in Erh-Chung wetlands.

MATERIAL AND METHODS

Description of Study Region

The Erh-Chung wetlands are located south of Taipei city (121°25'~121°27'N, 25°04'~25°06'E, Figure 1) near the Tang-sui River. This wetland area consists of 320 surface ha at an average depth of 0.88 m. The area was farmed until over pumping of groundwater during 1950 to 1960 caused the land to sink, and invasive tides from the Tang-sui River flowed into the area forcing farmers to abandon crop cultivation due to soil salinity. After 1970, the area become a wetland and a habitat for wildlife. Domestic and industrial wastewaters, and seepage water from landfills, have caused serious pollution problems. Water inflow of the study site include the Chung-Kang canal, the Wen-Tzu canal and incoming wastewater with conductivities that range from 572 to 17,790 μs/cm. Sixty to seventy percent of the free water surface of the Wen-Tzu canal is covered by water hyacinth plants.

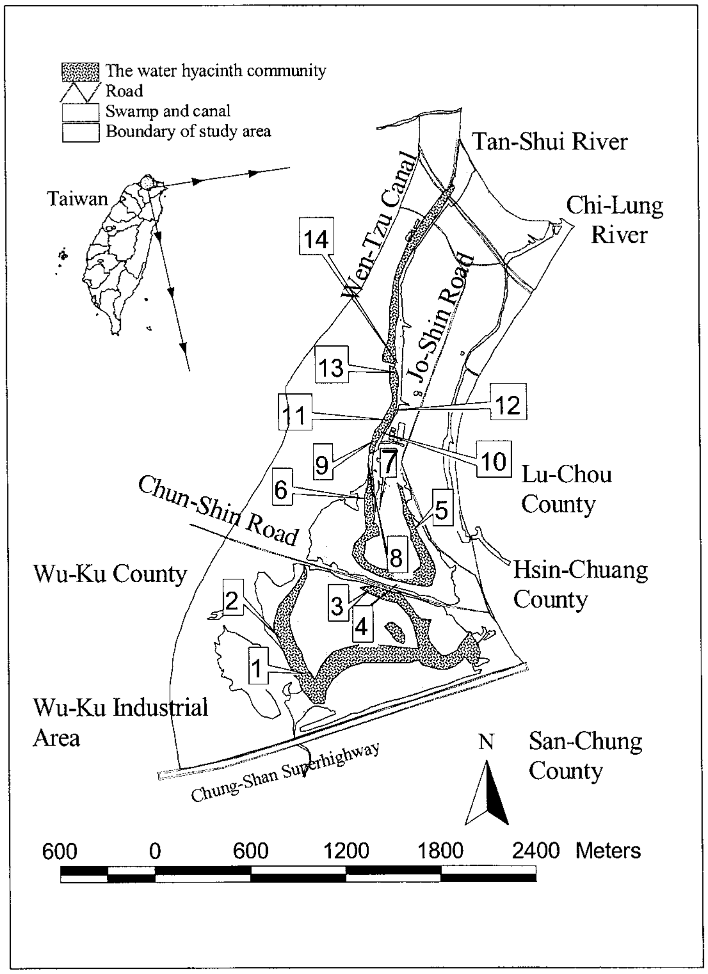

Figure 1. Sampling stations at Urh-Chung wetland, Taiwan.

Water, Sediment, and Plant Sampling

The main area of interest was along the Wen-Tzu canal and the flood plain region, located in the southern part of the Erh-Chung wetlands. The first sampling was during ebb tides in February 1998 at sampling stations No. 1 to 6. The second set of samples was taken during rising tides in March 1998 at sampling stations No. 7 to14. At each sampling station, surface water, sediment, and water hyacinth plants were sampled.

Analytical Methods

Water samples were collected in plastic bottles that had been previously soaked in 10% nitric acid for 48 hours and thoroughly rinsed with deionized-distilled water. All samples were filtered using 0.45 μm cellulose acetate filters, and acidified to pH 2 with nitric acid in the laboratory. Sediment samples were air-dried at 30 C and pounded to pass a 2-mm sieve. Using a 1:1 soil-water extraction ratio, the sediment was digested as described elsewhere (Goncalves and Boaventura 1991). The concentrations of Cu, Cd, Ni, Pb, and Zn were analyzed by ICP-AES (ICP LIBERTY) with an ultrasonic nebulizer. The minimum detection limits were found to be 1.3, 1.2, 2.4, 3.2, and 1.3, μg/kg, respectively.

At least three separate water hyacinth plants were collected at each sampling station. The plants were collected into clean plastic bags, previously soaked in dilute nitric acid and thoroughly rinsed with deionized-distilled water. In the laboratory, the plants were carefully washed with distilled water and then divided into tops and roots, and dried for 12 hours at 120 C in a forced air oven (Brower et al. 1997). The samples were then ground to a fine powder using a silica pestle and mortar, and the heavy metals were digested and analyzed by ICP-AES (ICP LIBERTY) with an ultrasonic nebulizer.

Bioconcentration Factor and Translocation Ability

The bioconcentration factor (BCF) was calculated as the ratio of the trace element concentration in the plant tissues at harvest to the concentration of the element in the external environment (Zayed et al. 1998). BCF is given by,

$$BCF = (P/E)_i \qquad (1)$$

where i denotes the heavy metal, and BCF is the bioconcentration factor and is dimensionless. P represents the trace element concentration in plant tissues (mg kg^{-1} dry wt); E represents the trace element concentration in the water (mg L^{-1}) or in the sediment (mg kg^{-1} dry wt). A larger ratio implies better phytoaccumulation capability.

Translocation ability (*TA*) was calculated by dividing the concentration of a trace element accumulated in the root tis-

TABLE 1. CORRELATION MATRIX BETWEEN TRACE ELEMENTS ACCUMULATED IN PLANT TISSUES AND BCF IN DIFFERENT EXTERNAL ENVIRONMENTS. FOR ABBREVIATIONS PLEASE SEE MATERIAL AND METHODS.

		Cd_w	Cd_s	Cd_{ps}	Cd_{pr}	BCF_{wps}	BCF_{sps}	BCF_{wpr}	BCF_{spr}
Cd	Cd_w	1.00							
	Cd_s	(0.47)	1.00						
	Cd_{ps}	(0.55)	0.63	1.00					
	Cd_{pr}	0.35	(0.13)	0.24	1.00				
	BCF_{wps}	(0.62)	0.51	0.52	(0.37)	1.00			
	BCF_{sps}	0.07	(0.71)	0.01	0.36	(0.19)	1.00		
	BCF_{wpr}	(0.73)	0.65	0.64	(0.17)	0.88	(0.20)	1.00	
	BCF_{spr}	0.53	(0.76)	(0.32)	0.69	(0.51)	0.76	(0.47)	1.00
		Cu_w	Cu_s	Cu_{ps}	Cu_{pr}	BCF_{wps}	BCF_{sps}	BCF_{wpr}	BCF_{spr}
Cu	Cu_w	1.00							
	Cu_s	0.67	1.00						
	Cu_{ps}	0.66	0.51	1.00					
	Cu_{pr}	0.06	0.06	0.69	1.00				
	BCF_{wps}	(0.51)	(0.29)	0.30	0.71	1.00			
	BCF_{sps}	(0.22)	(0.37)	0.25	0.77	0.56	1.00		
	BCF_{wpr}	(0.51)	(0.32)	0.23	0.81	0.92	0.77	1.00	
	BCF_{spr}	(0.24)	(0.31)	0.23	0.78	0.57	0.98	0.79	1.00
		Ni_w	Ni_s	Ni_{ps}	Ni_{pr}	BCF_{wps}	BCF_{sps}	BCF_{wpr}	BCF_{spr}
Ni	Ni_w	1.00							
	Ni_s	(0.08)	1.00						
	Ni_{ps}	(0.39)	(0.25)	1.00					
	Ni_{pr}	0.33	0.07	0.14	1.00				
	BCF_{wps}	(0.69)	(0.32)	0.81	(0.20)	1.00			
	BCF_{sps}	(0.27)	(0.49)	0.89	(0.03)	0.77	1.00		
	BCF_{wpr}	(0.78)	(0.28)	0.69	(0.22)	0.97	0.64	1.00	
	BCF_{spr}	0.10	(0.62)	0.61	0.11	0.40	0.85	0.29	1.00
		Pb_w	Pb_s	Pb_{ps}	Pb_{pr}	BCF_{wps}	BCF_{sps}	BCF_{wpr}	BCF_{spr}
Pb	Pb_w	1.00							
	Pb_s	0.08	1.00						
	Pb_{ps}	0.71	0.13	1.00					
	Pb_{pr}	0.10	(0.02)	(0.02)	1.00				
	BCF_{wps}	(0.77)	(0.01)	(0.27)	(0.42)	1.00			
	BCF_{sps}	0.15	(0.69)	0.46	(0.16)	0.05	1.00		
	BCF_{wpr}	(0.86)	0.01	(0.48)	(0.06)	0.87	(0.19)	1.00	
	BCF_{spr}	(0.12)	(0.76)	(0.16)	0.53	(0.15)	0.56	0.01	1.00
		Zn_w	Zn_s	Zn_{ps}	Zn_{pr}	BCF_{wps}	BCF_{sps}	BCF_{wpr}	BCF_{spr}
Zn	Zn_w	1.00							
	Zn_s	(0.06)	1.00						
	Zn_{ps}	0.32	0.51	1.00					
	Zn_{pr}	0.28	0.23	0.57	1.00				
	BCF_{wps}	(0.34)	0.58	0.70	0.35	1.00			
	BCF_{sps}	0.43	(0.42)	0.44	0.31	0.15	1.00		
	BCF_{wpr}	(0.76)	0.00	(0.21)	0.27	0.39	(0.21)	1.00	
	BCF_{spr}	0.49	(0.67)	(0.10)	0.24	(0.29)	0.73	(0.09)	1.00

sues by that accumulated in shoot tissues (Wu and Sun 1998). *TA* is given by,

$$TA = (A_r/A_s)_i \quad (2)$$

where *i* denotes the heavy metal. *TA* is the translocation ability and is dimensionless. A_r represents the amount of trace element accumulated in the roots (mg kg^{-1} dw), and A_s represents the amount of trace element accumulated in the shoots (mg kg^{-1} dw). A larger ratio implies poorer translocation capability.

RESLUTS AND DISCUSSION

Phytoaccumulation and Bioconcentration Factor

Table 1 presents the correlation matrix regarding the bioaccumulation and bioconcentration in plant roots and shoots of water hyacinth. Table 2 explains the notations used in Table 1 and Figures 2-6. The five trace elements concentration in water was positively correlated with the amount accumulated in the plant roots (Table 1) indicating the water hyacinth plants absorbed these trace elements more easily from water than from sediment. Cd had the least level of accumulation as compared to other four trace elements in water or in sediment. When the external concentration reached the maximum of 0.06 mg L^{-1}, the maximum accumu-

TABLE 2. ABBREVIATIONS USED IN TABLE 1 AND FIGURES 2-6.

Notation	Interpretation of notations
Cd_w	Cd concentration in water, mg L^{-1}
Cd_s	Cd concentration in sediment, mg kg^{-1}-dw
Cd_{ps}	Cd accumulation in plant shoots, mg kg^{-1}-dw
Cd_{pr}	Cd accumulation in plant roots, mg kg^{-1}-dw
BCF_{wps}	bioconcentration factor of heavy metal in plant shoots from water, dimensionless
BCF_{sps}	bioconcentration factor of heavy metal in plant shoots from sediment, dimensionless
BCF_{wpr}	bioconcentration factor of heavy metal in plant roots from water, dimensionless
BCF_{spr}	bioconcentration factor of heavy metal in plant roots from sediment, dimensionless

Note: the other trace elements' definitions were the same as Cd.

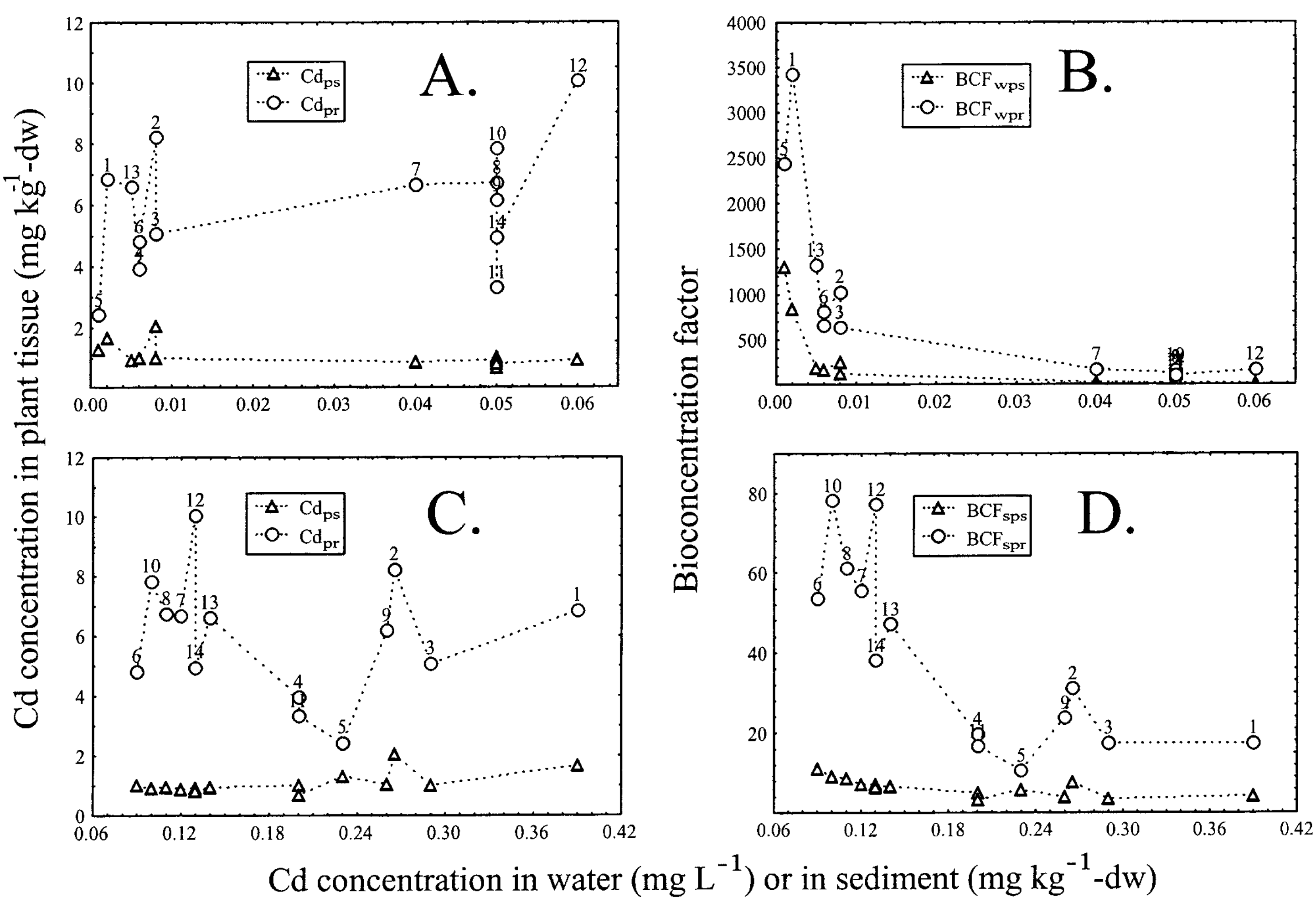

Figure 2. (1) A and B show the influence of increasing content of Cd in water; C and D show in sediment. (2) A and C show the accumulation rate; B and D show the bioconcentration factor of Cd in water hyacinth. Number 1-14 in figures is the sampling site. Note: notation please see Table 2.

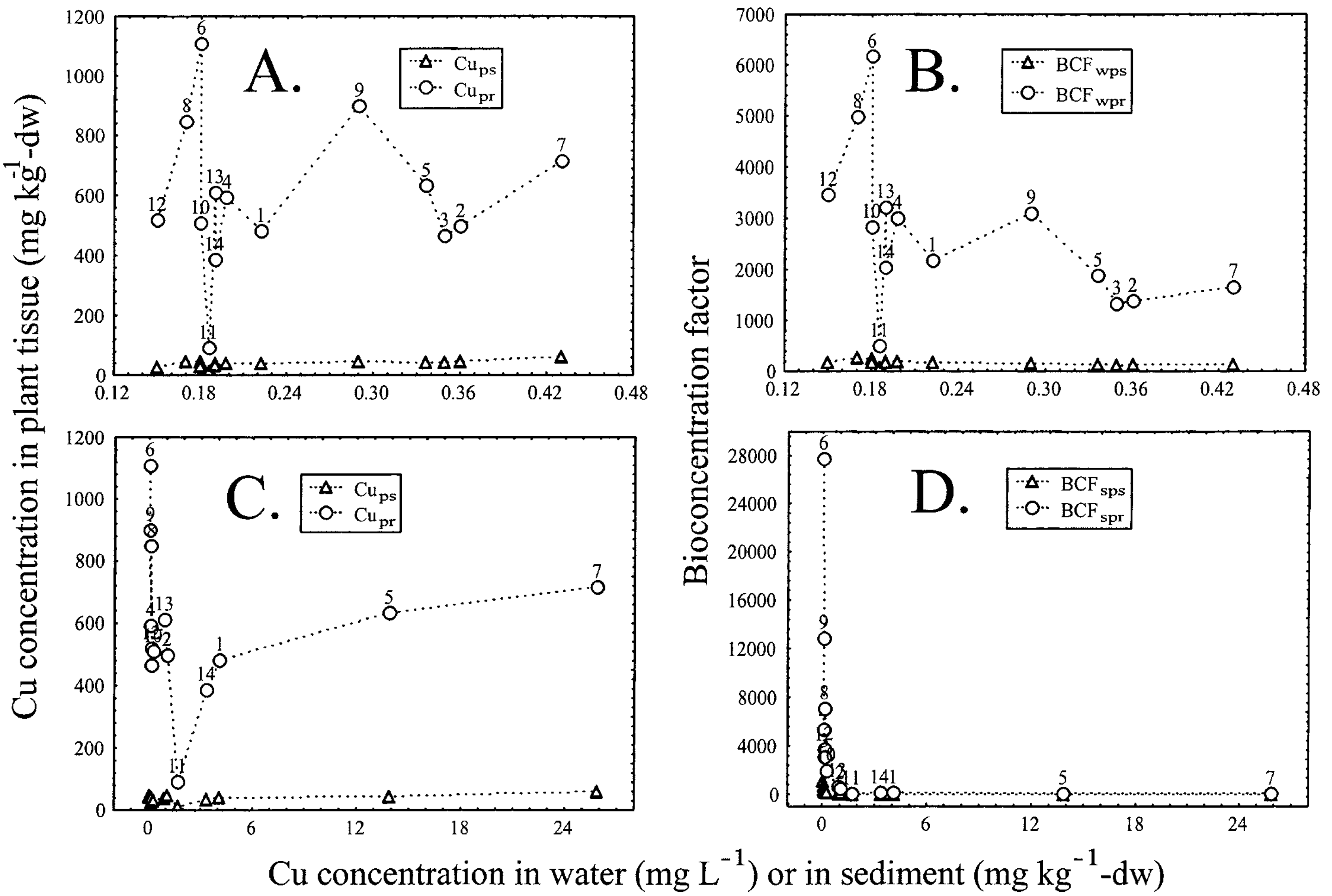

Figure 3. (1) A and B show the influence of increasing content of Cu in water; C and D show in sediment. (2) A and C show the accumulation rate; B and D show the bioconcentration factor of Cu in water hyacinth. Number 1-14 in figures is the sampling site. Note: notation please see Table 2.

lation in the roots was 10.05 mg kg^{-1} dw, this capacity of rhizofiltration was lower than studied by Zhu et al. (1999) (Figure 2A). The BCF in shoots exceeded 1,000 at low concentration in water only for Cd (Figure 2B). About 10 to 20 times more Cd accumulated in the roots than in the shoots (Figure 2C). The BCF of Cd in sediment was lower than that of the other four elements especially in plant shoots (Figure 2D). Meanwhile, this value was also lower than other wetland plant species (Zayed et al. 1998, Rai et al. 1995).

The accumulation of Cu was 1,110 mg kg^{-1} dw. This amount was the highest level as compared to other four trace elements accumulated in the plant roots but lower than that reported by Low et al. (1994) and Gupta et al. (1994) in different plant species (Figure 3A). The BCF decreased slowly in the shoots, unlike the other elements, dropped abruptly (Figure 3B). The Cu concentration in roots was about 7 to 24 times higher than in shoots (Figure 3C). The highest level of BCF for Cu in sediment found in the shoots and roots were 1,147 and 27,745, respectively, were the highest levels of BCF compared to other four trace elements (Figure 3D). Cd and Ni concentration in water was negatively correlated with the amount accumulated in the shoots only (Table 1). Although the concentration of Ni exceeds Zn in the water environment, the absorption of Ni in the shoots was less than that of Zn (Figure 4A). At Ni in a low concentration of 0.16 mg L^{-1}, the highest levels of BCF in shoots compared other four trace elements was 1,369 (Figure 4B). In a sediment environment, only Ni had negative correlation with shoot accumulation (Figure 4C). The BCF of Ni was quite small in plant shoots and roots when external environment was in the sediment (Figure 4D).

The amount of Pb accumulated in the roots was about 4 to 16 times higher than that in the shoots (Figure 5A). When the Pb concentration was lowest at 0.03 mg L^{-1}, the BCF in the shoots and roots was highest, at 555 and 4,333, respectively (Figure 5B). The highest levels of accumulation for Pb in plant roots and shoots were 215.35 and 33.34 mg kg^{-1} dw, respectively, and their ability for accumulation was greater than *Brassica juncea* (L.) Czern (Dushenkov et al. 1995, Kumar et al. 1995) (Figure 5C). The rhizofiltration of Pb by water hyacinth (Figure 5D) in the Erh-Chung wetland was greater than many different plant species compared to Dushenkov et al. (1995).

Zn concentrations in the roots were about 1.5 to 5 times higher than that in the shoots (Figure 6A), and its accumulation was less only than that of Cu. This was different compared to previous observation by Dirilgen and Inel (1994),

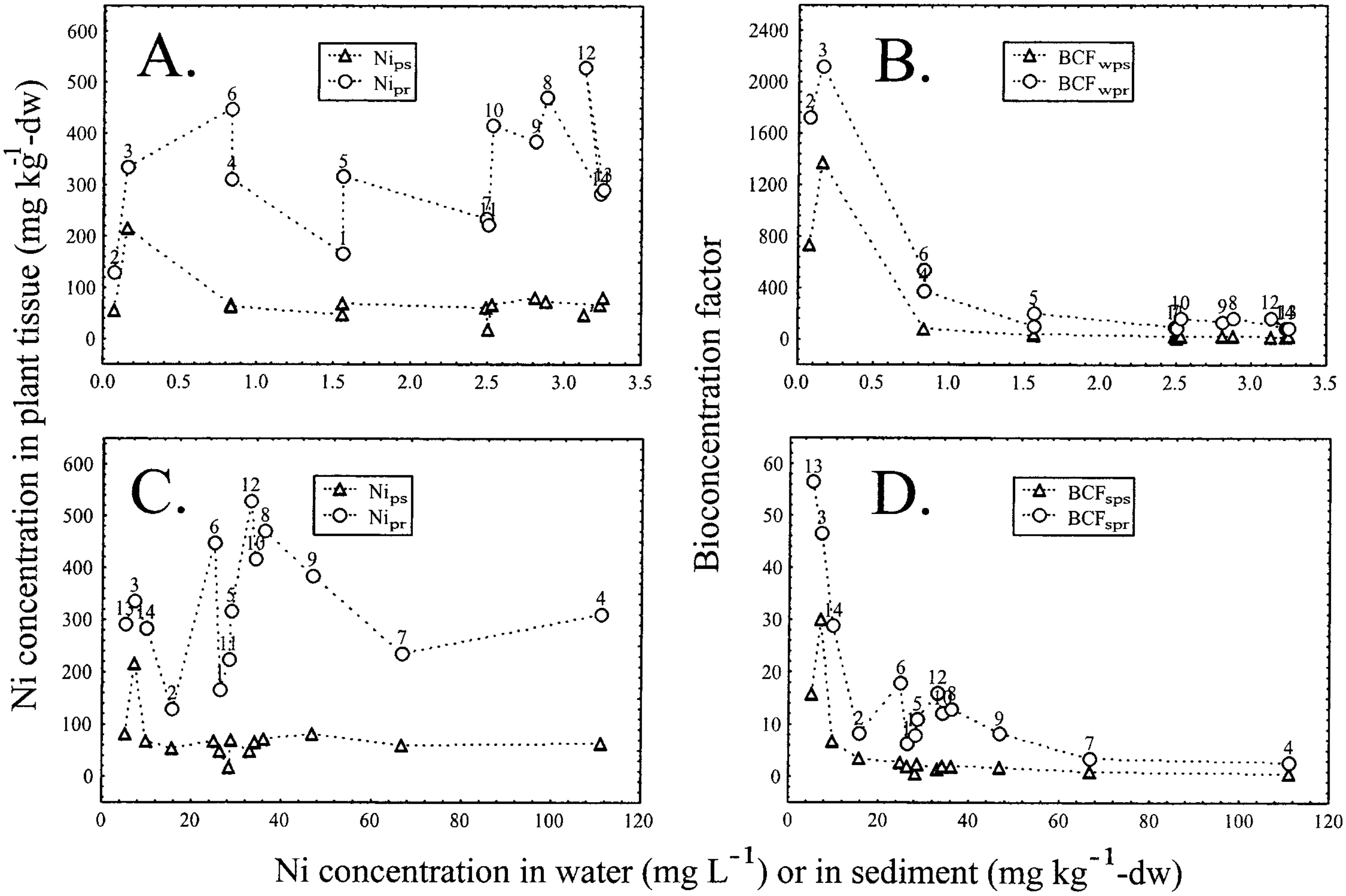

Figure 4. (1) A and B show the influence of increasing content of Ni in water; C and D show in sediment. (2) A and C show the accumulation rate; B and D show the bioconcentration factor of Ni in water hyacinth. Number 1-14 in figures is the sampling site. Note: notation please see Table 2.

which was in different plant species and under controlled laboratory conditions. Sediment accumulated Zn to the highest level compared the other four elements tested (Figure 6C). However, the BCF in shoots and roots was the lowest compared other four trace elements when the external concentration Zn was highest at 554.75 mg kg^{-1} dw (Figure 6D).

Translocation Ability and the Effectiveness of BCF

The quantities of trace elements accumulated in the roots exceeded those in the shoots. Roots of water hyacinth accumulated about 3 to 15 times more trace elements than did the shoots. The quantities of accumulation were in the order, Zn > Ni >Cu > Pb > Cd in the shoots, and Cu > Zn > Ni > Pb > Cd in the roots. Different findings were reported for the uptake of heavy metals by water hyacinth (Zayed et al. 1998, Zaranyika and Ndapwadza 1995, Low et al. 1994). Translocation ability was calculated by dividing the concentration of a trace element accumulated in the root tissues by that accumulated in shoot tissues. Translocation capability of these five heavy metals was in the order of Cu (14.77 ± 4.56) Pb (8.56 ± 3.17) Cd (5.84 ± 2.27) Ni (5.44 ± 3.05) Zn (3.37 ± 1.27). A larger number of translocation ability implies a poorer translocation capability. Water hyacinth absorbed the heavy metals mostly from the roots and translocated only 6 to 25% to the shoots. Poorer translocation ability was found in a pilot plan (Soltan and Rashed 2003).

According to Zhu et al. 1999, a good accumulator is recognized by two criteria in experiment conditions—(a) its ability to take up concentration more than 5,000 mg kg^{-1} dw of a given element, and (b) its ability to bioconcentrate the element in its tissues; for example, the BCF value exceeds 1,000. In our study, water hyacinth did not absorb trace elements greater than 5,000 mg kg^{-1} dw. Therefore, only the BCF in plant root was considered to evaluate the effectiveness of water hyacinth as a phytoremediator. The shoots met the criteria only for Cd at the low concentration in water. When the external environment had a low concentration of Cu level at 0.18 mg L^{-1}, the BCF of roots was highest at 6,166. This result differed from that reported by Zhu et al. (1999), who found that water hyacinth best accumulated the Cd trace element. The highest level of BCFs in water was greater than report by Zaranyika and Ndapwadza (1995), except for Zn in Mukuvisi River. The BCF of trace element in water exceeded those in sediment, except for Cu. When Cu was in low concentration in the sediment, the bioconcentration effect of Cu exceeded

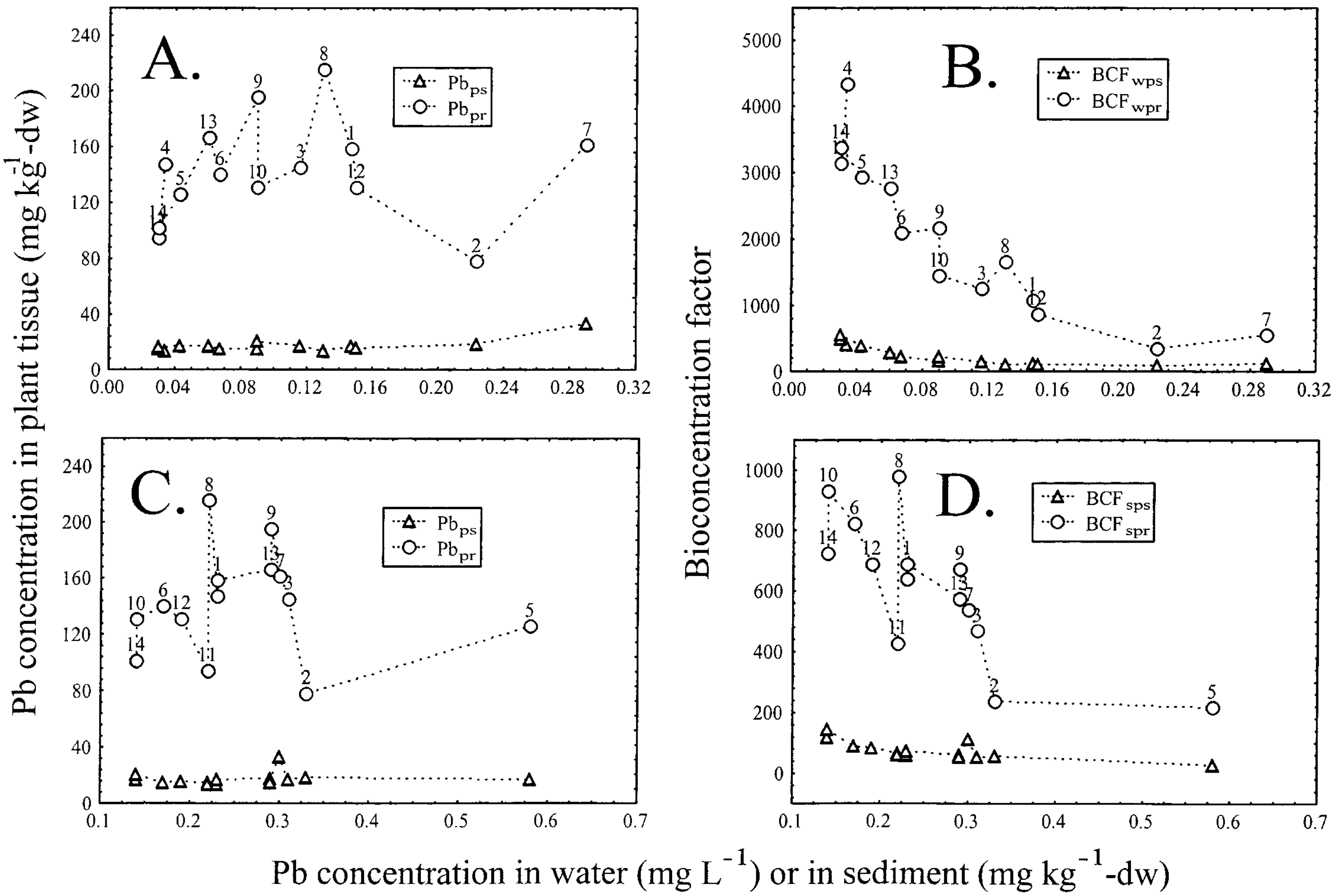

Figure 5. (1) A and B show the influence of increasing content of Pb in water; C and D show in sediment. (2) A and C show the accumulation rate; B and D show the bioconcentration factor of Pb in water hyacinth. Number 1-14 in figures is the sampling site. Note: notation please see Table 2.

that of all other trace elements, and the BCFs for all other trace elements were lower than 1,000. Thus, the roots of water hyacinth effectively bioconcentration Cu and have a good phytoremediation effect at low concentrations whether in the water or in the sediment. Cd, Cu, Ni, Pb, and Zn were associated with large BCF at low concentrations the same as selenium (Carvalho and Martin 2001). Heavy metals, except Cu, were absorbed by water hyacinth more efficiently from water than from sediment in shallow water. As regard with the BCFs, water hyacinth is effective to absorb and accumulate trace elements in plant roots only for Cu from sediment. Furthermore, the BCF for Pb reveals partial effectiveness at low concentrations in the sediment. Other elements such as Cd, Ni, and Zn are less effectively bioconcentrated as the corresponding BCF values were less than 100.

THE CAPACITY OF ACCUMULATION

In one growing season, 64.5 kg wet weight of water hyacinth per square meter can be produced (Wooteh and Dodd 1976). From this estimate, the absorption and accumulation per unit area of each trace element can be calculated. The value is 24 mg m^{-2} for Cd, 542 mg m^{-2} for Pb, 2162 mg m^{-2} for Cu, 2617 mg m^{-2} for Zn, and 1346 mg m^{-2} for Ni, respectively. In our study, by applying the ARC/INFO software techniques (ESRI 1997), the absorption capacity in the Erh-Chung wetlands was 0.2 kg ha^{-1} for Cd, 5.4 kg ha^{-1} for Pb, 21.6 kg ha^{-1} for Cu, 26.2 kg ha^{-1} for Zn, and 13.5 kg ha^{-1} for Ni, respectively. An on-site investigation differs from an experimental laboratory investigation in many ways, because of the impact of various factors, such as microclimate, hydrology, soil physics, soil chemistry, and soil biology. Our study provides quantitative information using water hyacinth to remove heavy metals in the Erh-Chung wetland, and lays the foundations for more detailed experimental work.

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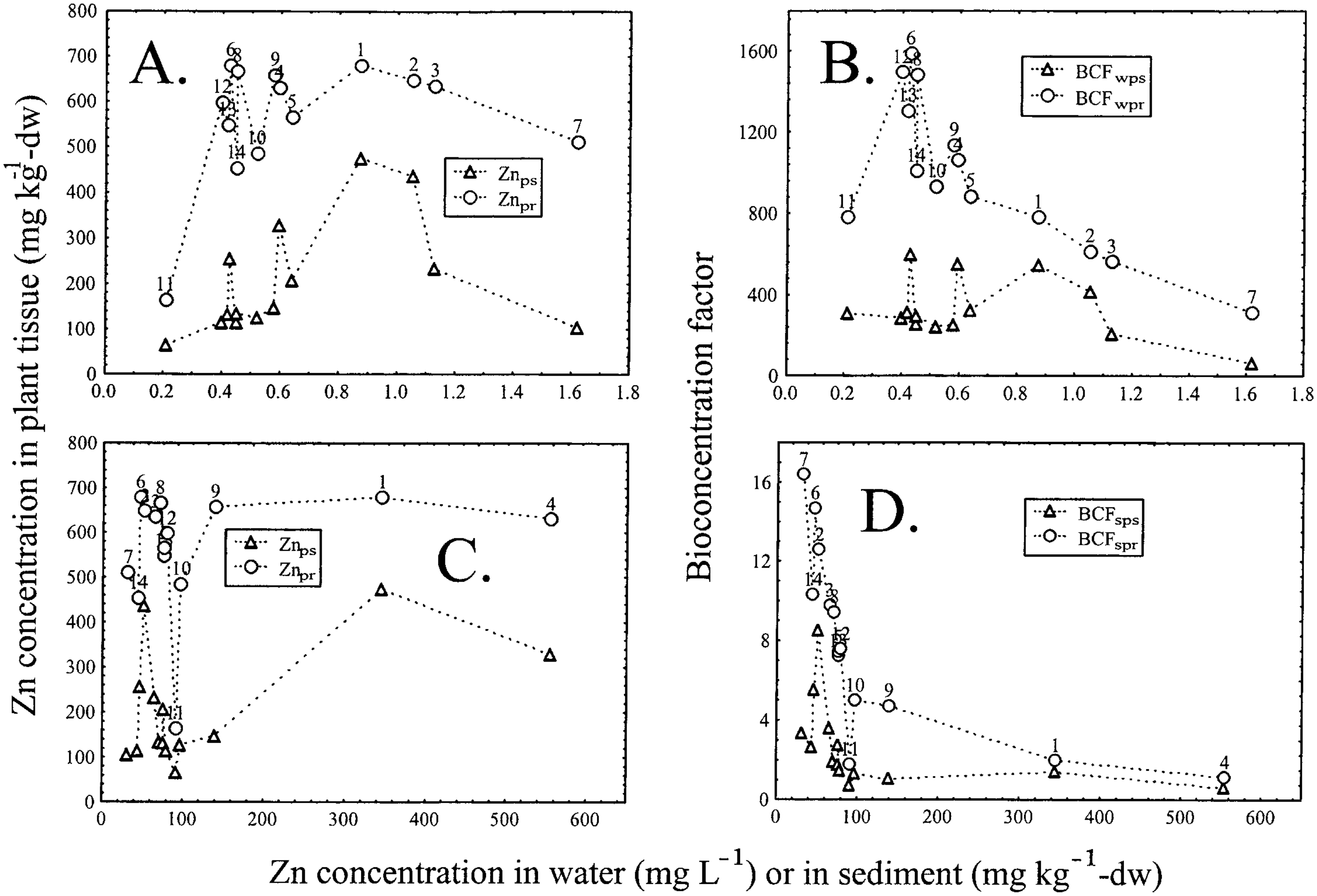

Figure 6. (1) A and B show the influence of increasing content of Zn in water; C and D show in sediment. (2) A and C show the accumulation rate; B and D show the bioconcentration factor of Zn in water hyacinth. Number 1-14 in figures is the sampling site. Note: notation please see Table 2.

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