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Phytoremediation efficiency of crop plants in removing cadmium, lead and zinc from soil

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ABSTRACT

The experiment was carried out in 1999-2001 at the University of Agriculture in Krakow (Poland) to study the capacity of nine crops (red beet, field pumpkin, chicory, bean, barley, white cabbage, maize, alfalfa, and parsnip) to remove cadmium (Cd), lead (Pb) and zinc (Zn) from different soil horizons (0-20, 20-40, 40-60 cm). The content of exchangeable Cd, Pb, and Zn decreased along with the depth in the soil profile. Red beet cultivation reduced the exchangeable Cd content in the soil by 10.3% and by 8.6% in field pumpkin, barley and maize cultivation in the 0-20 cm horizon. White cabbage and maize decreased Cd in the 20-40 cm horizon by 40.0 and 28.8%, respectively. White cabbage was found to be the most effective in removing Pb from the soil profile. Common bean, maize, and alfalfa reduced exchangeable Pb in two upper horizons of the soil: 0-20 and 20-40 cm. After field pumpkin cultivation, the decrease in Pb contamination in the 0-20 cm horizon was 7.4%. White cabbage and chicory reduced exchangeable Zn content in the surface horizon by 21.5 and 14.1%, respectively. According to their efficiency in metal reduction, maize and red beet may be indicated as potential removers of Cd, cabbage and field pumpkin, of Pb, and cabbage, of Zn.

Key words: alfalfa, barley, bean, chicory, field pumpkin, heavy metals, maize, parsnip, phytoextraction, red beet, white cabbage

INTRODUCTION

The removal of heavy metals from soil using green plants, called phytoremediation, has been described by Cunningham et al. (1995) and Salt et al. (1995, 1998). To achieve a significant reduction of contaminants within one or two decades, it is necessary to use hyperaccumulators (plants capable of accumulating >100 mg Cd kg^{-1}, >1000 mg Pb kg^{-1}, and >10 000 mg Zn kg^{-1} in the dry matter of their shoots when growing in their natural habitats) or crops with a metal bioconcentration factor (which is the ratio of metal concentration in the shoot tissue to the metal concentration in the soil) of 20 and a biomass production of 10 tons per hectare, or with a metal bioconcentration factor of 10 and a biomass production of 20 t ha^{-1} (Baker et al. 1994, McGrath and Zhao 2003, Peuke and Rennenberg 2005). Ciura et al. (2005), Poniedziałek et al. (2005 a, b) and Sękara et al. (2005 a, b) proposed to use cultivated species that produce a large biomass, and simultaneously accumulate metals in non-edible parts, in phytoremediation. Wang et al. (2002) conducted field and glasshouse investigations to study the response of two legumes (field pea and fodder vetch) and three non-leguminous crops (maize, wheat, and rapeseed) to the heavy metals (Cd, Cr, Zn, Pb, Cu and Mn) in the soil with multiple metal contamination. In addition, Ishikawa et al. (2006) evaluated the ability of *Brassica juncea* L., which has already been recognized as a plant suitable for metal phytoremediation, and of several other cultivated plant species (maize, rice, and sugar beet), to extract cadmium from soils with moderately low levels of Cd contamination.

Numerous factors control metal uptake by plants; for example, density of absorption sites on the root membranes, rapid transport within the plant, the proliferation of roots in metal hotspots within the soil, acidification of the rhizosphere, and the release of phytometallophores into the rhizosphere (Hutchinson et al. 2000). Zinc and cadmium are ubiquitous pollutants that tend to occur together at many contaminated sites. While Zn is often phytotoxic, Cd rarely inhibits plant growth (Alkorta et al. 2004). Cd is one of the more mobile heavy metals in the soil-plant system, easily taken up by plants and with no essential function known to date (Lehoczky et al. 2000). In the soil, it is easily mobile in a pH range of 4.5-5.5, while at higher pH values it turns into insoluble carbonate and phosphate forms (Kabata-Pendias 2000). In a soil solution, cadmium often occurs as the Cd^{2+} ion, but it can also create complex ions. The complex ion with Cl^- is easily mobile and available to plants. When soil pH increases, $CdOH^+$ ions are bound more strongly by organic colloids, aluminum, and iron oxide. This process lowers cadmium availability to plants (Patorczyk-Pytlik and Spiak 2000). Ciura et al. (2005) showed that the crop's efficiency in cleaning soil polluted with Cd was dependent on its biomass production and the metal distribution among its crop tissues.

Lead belongs to those elements that are poorly mobile and rarely available to plants. However, it may create different organic and inorganic compounds, easily absorbed by roots. In soil, Pb cations are frequently absorbed by iron, manganese and nickel hydroxides, as well as by organic matter (Wang et al. 2003). A model for the uptake, translocation, and accumulation of Pb by maize for the purpose of phytoextraction has been proposed, suggesting that the precipitation of Pb as a Pb-phoshate is one of the most important mechanisms in this system, with a maximum saturable uptake rate of Pb and effective roots mass also existing as possible key plant parameters (Brennan and Shelley 1999). Sękara et al. (2005 a) found significant differences between crops in their ability to accumulate Pb in tissue and their phytoremediation efficiency. In red beet, field pumpkin, chicory, common bean, white cabbage, and parsnip the maximum Pb content was found in the leaves. The red beet and common parsnip were characterized by the highest Pb shoots/roots concentration ratios.

Zinc content in soil amounts to 10-120 mg kg^{-1}. Plants may accumulate Zn in above-ground biomass and its concentrations increase with the increase of soil-bound Zn (Ernst and Nielssen 2000). However, Ciura et al. (2005) and Sękara et al. (2005 b) reported that field pumpkin effectively remediated Zn from the soil because of a high biomass production. In addition it was found that barley considerably exceeded the remaining species in Zn bioaccumulation, but because of its inadequate biomass production, it was not considered as an effective Zn extractor. Wang et al. (2003) reported the discovery of two new plants with potential for phytoremediation of Zn-polluted soils, i.e., *Polygonum hydropiper* and *Rumex acetosa*. In the same study, the authors indicate that the consumption of rice grown in paddy soils contaminated with Cd, Cr or Zn may pose a serious risk to human health, as 22 to 24% of the total metal content in the rice biomass was concentrated in the rice grain. The lack of understanding pertaining to metal uptake and translocation mechanisms, enhancement amendments, and external effects of phytoremediation is hindering its full scale application. Due to its great potential as a viable alternative to traditional contaminated land remediation methods, phytoremediation is currently an exciting area of active research (Alkorta et al. 2004).

The aim of the present investigation was to examine the capacity of nine crops to remediate cadmium, lead, and zinc from different soil layers.

MATERIAL AND METHODS

A field experiment was conducted at the University of Agriculture in Krakow (Poland) in 1999-2001, on soil classified as *Eutric Cambisol* with loess as the basement complex, pH_{KCl} 4.8, 1.2% organic carbon, and a sorption capacity of 29.6 me 100 g^{-1}. Nine crops were planted on experimental plots (9 m^2) using a random block design with four replications: red beet (*Beta vulgaris* var. *canditiva* L.) – 'Wodan F_1'; field pumpkin (*Cucurbita pepo* L. convar. *giromontiana* Greb.) – 'Astra F_1'; chicory (*Cichorium intybus* var. *foliosum* Hegi) – 'Rubello F_1'; common bean (*Phaseolus vulgaris* L.) – 'Tara'; barley (*Hordeum vulgare* L.) – 'Stat'; white cabbage (*Brassica oleracea* var. *capitata* L.) – 'Krautman F_1'; maize (*Zea mays* L. convar. *saccharata* Koern.) – 'Trophy F_1'; alfaalfa (*Medicago sativa* L.) –

'Vela', and common parsnip (*Pastinaca sativa* L.) – 'Półdługi Biały'.

Before the start of the experiment and after the harvesting of crops, the exchangeable content of cadmium, lead and zinc was determined in soil samples collected from the 0-20, 20-40, and 40-60 cm layers. Soil samples (10 g) were treated with 100 cm^3 0.01 M $CaCl_2$ and shaken for two hours. After the filtration of the solids, Cd, Pb, and Zn were obtained by the ASA method, using the Varian-SpectrAA 20 and an air/acetylene flame under standard operating conditions.

The results were statistically evaluated using ANOVA at $p \leq 0.05$. Regression analysis was performed and the coefficients of simple correlation (r) were calculated between the level of metals in the soil and the amount of metal absorbed by plants from 1 m^2 and between the level of metals in the soil and the plant biomass yield. The starting data on plant biomass yield, and the total metal removed from the soil by each plant species used in the analysis of regression were published by Ciura et al. (2005).

RESULTS AND DISCUSSION

Soil pH, other factors such as the presence of competing ligands, the ionic strength of the soil solution and the simultaneous presence of competing metals are known to significantly affect the sorption processes of particular elements through a soil profile (Harter and Naidu 2001). In the present study, exchangeable cadmium, lead and zinc concentrations decreased with depth in the soil profile and the highest amounts of these metals were found in the surface horizon (Tabs 1-3). In the 0-20 cm horizon, lead content was four times higher than at 40-60 cm, and two times higher than at the 20-40 cm horizon, which confirmed Li and Shuman's (1996) observations. The cited authors

Table 1. The exchangeable Cd content in soil at different horizons, means for 1999-2001

		Cd (mg kg^{-1})		
Soil horizon (cm)		0-20	20-40	40-60
Before vegetation		0.58 bc*	0.45 e	0.22 a
After vegetation of:	Red beet	0.52 a	0.43 de	0.22 a
	Field pumpkin	0.53 a	0.42 cd	0.22 a
	Chicory	0.60 c	0.41 c	0.22 a
	Common bean	0.58 bc	0.45 e	0.22 a
	Barley	0.53 a	0.43 e	0.23 a
	White cabbage	0.54 ab	0.27 a	0.22 a
	Maize	0.53 a	0.32 b	0.22 a
	Alfalfa	0.56 abc	0.43 de	0.23 a
	Common parsnip	0.54 ab	0.41 e	0.22 a

*Values within columns followed by the same letters do not differ significantly at $p \leq 0.05$

Table 2. The exchangeable Pb content in soil at different horizons, means for 1999-2001

		Pb (mg kg^{-1})		
Soil horizon (cm)		0-20	20-40	40-60
Before vegetation		8.21 c*	5.13 e	2.72 b
After vegetation of:	Red beet	8.22 c	5.09 de	2.79 bc
	Field pumpkin	7.60 a	4.80 cde	2.57 ab
	Chicory	7.99 bc	4.91 cde	2.68 b
	Common bean	7.83 ab	4.60 cd	2.67ab
	Barley	8.12 c	5.02 cde	2.76 bc
	White cabbage	7.66 a	3.58 a	2.36 a
	Maize	7.73 ab	4.17 b	2.69 b
	Alfalfa	7.84 ab	4.53 bc	3.05 c
	Common parsnip	7.83 ab	4.74 cde	2.48 ab

*Explanations: see Table 1

Table 3. exchangeable Zn content in soil at different horizons, means for 1999-2001

		Zn (mg kg^{-1})		
Soil horizon (cm)		0-20	20-40	40-60
Before vegetation		42.96 d	26.73 ab	14.22 a
After vegetation of:	Red beet	38.94 bcd	26.65 ab	13.87 a
	Field pumpkin	38.14 bc	25.68 ab	13.70 a
	Chicory	36.90 ab	27.08 b	14.30 a
	Common bean	42.70 d	26.93 b	14.10 a
	Barley	40.84 bcd	24.81 ab	14.08 a
	White cabbage	33.73 a	23.45 a	13.98 a
	Maize	40.43 bcd	24.76 ab	14.08 a
	Alfalfa	39.66 bcd	25.02 ab	13.52 a
	Common parsnip	41.09 cd	26.55 ab	14.17 a

*Explanations: see Table 1

reported that cadmium and lead were accumulated in topsoil because of their affinity with the organic matter fraction.

In the 0-20 cm horizon, red beet reduced exchangeable Cd by 10.3%, field pumpkin, barley and maize by 8.6%. White cabbage and maize decreased Cd in the 20-40 cm horizon, by 40.0 and 28.8%, respectively (Tab. 1). There were no statistical differences in cadmium content before and after the cultivation of all of the examined crops in the 40-60 cm horizon. White cabbage significantly decreased the level of exchangeable Pb in the entire soil profile (Tab. 2). In addition, common bean, maize, and alfalfa reduced Pb, but only in the two upper horizons of 0-20 and 20-40 cm. After field pumpkin cultivation the decrease in Pb contamination was 7.4%. Changes in exchangeable Zn content were the most significant at the 0-20 cm depth. Only white cabbage and chicory reduced Zn contamination in the surface horizon by 21.5 and 14.1%, respectively (Tab. 3). There were no significant differences between zinc content in soil before and after cultivation of the remaining species in the 20-40 and 40-60 cm horizons. Hutchinson et al. (2000) suggest that the restricted bioavailability of metals in contaminated soils may be a major limitation to the efficiency of this form of phytoextraction. Sun et al. (2007) investigated sugar beet (*Beta vulgaris*), mustard (*Brassica juncea* L.), and cabbage (*Brassica oleracea* L. var. *capitata* L.) as potential phytoremediants. Results from this study showed that these plants could extract heavy metals from soil, but the accumulation and translocation of metals differed with the species of plant, categories of heavy metals, and some environmental conditions (e.g. nutrients). Also, only exchangeable fractions of soil heavy metals were taken into consideration in the present investigation, because such fractions are available for plants. The exchangeable fraction of heavy metals is variable in the vegetation period as a result of plant root development and meteorological conditions. A future extension of the research may bring additional results on the influence of crops on the total heavy metal content in the soil profile.

An interesting positive correlation was found between cadmium accumulated by maize and its level in the soil at the 0-20 and 20-40 cm horizons and the accumulated Cd and maize biomass yield (Tabs 4 and 5). It suggests that maize accumulated Cd from the entire soil profile proportionally to its level in the soil and Cd contamination did not reduce the maize biomass yield. Also, Wang et al. (2007) stressed that Cd accumulation in the roots and shoots of the two maize cultivars increased significantly with increasing Cd concentration and duration of treatment. The efficiency of phytoextraction is relative to the ability of the plant to grow on polluted soils and produce substantial biomass with high concentrations of target metals in the above-ground parts (Schwartz et al. 2001). In the present study, red beet biomass yield was also positively correlated with Cd levels in the soil, and had a negative correlation between Cd level in the soil and in red beet tissues indicated an active accumulation of cadmium from deeper soil layers by this species. Singh et al. (2007) reported *B. vulgaris* as a plant that is sensitive to heavy metal concentration. In the cited study, the metal pollution index (MPI) of both roots and shoots of *B. vulgaris* showed significant and negative relationships with the yield of the plants. In the present study,

Table 4. Simple correlation coefficients (r) between the level of metal in the soil and metal removed from soil by plant species

Species	Horizon 0-20 cm			Horizon 20-40 cm		
	Cd	Pb	Zn	Cd	Pb	Zn
Red beet	0.421	-0.195	-0.802*	-0.626*	0.113	-0.936*
Field pumpkin	-0.772*	-0.623*	0.703*	-0.419	0.894*	0.869*
Chicory	0.273	-0.203	0.311	0.661*	0.647*	0.361
Common bean	-0.016	0.676	-0.266	-0.136	-0.886*	-0.308
Barley	-0.716*	-0.548	-0.726*	-0.676*	0.263	-0.856*
White cabbage	0.196	0.209	0.608*	0.011	0.200	0.771*
Maize	0.980*	0.639*	0.308	0.907*	-0.429	0.402
Alfalfa	0.606*	0.741*	0.714*	0.236	-0.722*	0.936*
Common parsnip	0.613*	0.590*	0.714*	0.356	-0.359	0.927*

*r significant at $p \leq 0.05$

Table 5. Simple correlation coefficients (r) between the level of metal in soil and a plant biomass yield

Species	Horizon 0-20 cm			Horizon 20-40 cm		
	Cd	Pb	Zn	Cd	Pb	Zn
Red beet	0.964*	-0.699*	0.006	0.808*	-0.641	-0.046
Field pumpkin	-0.023	-0.353	0.641*	0.365	0.685*	0.831*
Chicory	0.744*	0.253	0.304	0.857*	-0.091	0.506
Common bean	0.447	0.401	-0.707*	0.198	-0.605*	-0.364
Barley	-0.866*	-0.466	0.290	-0.890*	0.270	-0.338
White cabbage	0.138	-0.409	0.619*	0.536*	0.651	0.924*
Maize	0.877*	0.510	0.026	0.886*	-0.305	0.312
Alfalfa	-0.186	0.134	-0.464	-0.473	-0.425	-0.649*
Common parsnip	-0.124	0.115	-0.523	-0.401	-0.408	-0.615*

*Explanations: see Table 4

a positive correlation was found between Pb levels in cabbage tissues and in the soil at all horizons. White cabbage accumulated Pb from the entire soil profile proportionally to its level in the soil and Pb contamination did not reduce the cabbage biomass yield. Also, field pumpkin did not react a decrease of biomass yield as a consequence of Pb soil contamination. The *Brassicaceae* is a family containing many metal-accumulating species. An important phenomenon revealed by Xian (1989) was that the relative amount of metal uptake by the cabbage was Zn > Pb > Cd, which agreed with their concentration order in the soil, but the uptake rate of the metals in the soils was Cd > Zn > Pb, agreeing with the solubility of the metals in the soil. The amount of uptake by cabbage also increased as the metal levels rose in the soil, which was confirmed by the results of the present study. In the case of barley, negative correlations were noted in the case of the mentioned parameters, which indicates active Cd accumulation by barley, biomass reduction as an effect of soil contamination, and a low tolerance of this species to Cd. Aery and Jagetiya (1997) studied the relative toxicity of Cd, Pb, and Zn on the growth performance of barley, and they noted a significant inverse relationship between relative plant yield and tissue element concentration. In the case of the remaining species investigated in the present study, correlations were not as obvious and they were limited to only one soil horizon. In metal reduction efficiency, maize and red beet may be indicated as potential remediants of Cd, cabbage and field pumpkin of Pb, and cabbage of Zn. This confirms the results of Ciura et al. (2005), who indicated that field pumpkin was a promising Cd, Pb, and Zn phytoextractor, based on its biomass production and total metal removed from soil in the plant biomass.

CONCLUSIONS

1. Exchangeable Cd, Pb, and Zn content in soil profile decreased along with depth.

2. Red beet reduced exchangeable Cd in the soil by 10.3% and field pumpkin, barley and maize by 8.6% in the 0-20 cm soil horizon. White cabbage and maize decreased Cd in the 20-40 cm horizon by 40.0 and 28.8%, respectively.
3. White cabbage was found to be the most effective in removing Pb from the entire soil profile. Common bean, maize, and alfalfa reduced soil Pb in two upper horizons, 0-20 and 20-40 cm. After field pumpkin cultivation the decrease in Pb contamination in the 0-20 cm horizon was 7.4%.
4. White cabbage and chicory reduced Zn contamination in the surface horizon by 21.5 and 14.1%, respectively.
5. In metal reduction efficiency, maize and red beet may be indicated as potential phytoremediants of Cd, cabbage and field pumpkin of Pb, and cabbage of Zn.

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MOŻLIWOŚĆ WYKORZYSTANIA ROŚLIN UPRAWNYCH W FITOREMEDIACJI GLEB ZANIECZYSZCZONYCH KADMEM, OŁOWIEM I CYNKIEM

Streszczenie: Badania prowadzono w latach 1999-2001 na Uniwersytecie Rolniczym w Krakowie, w celu określenia możliwości wykorzystania dziewięciu gatunków roślin uprawnych (burak ćwikłowy, dynia zwyczajna, cykoria, fasola zwyczajna, jęczmień, lucerna, kapusta głowiasta biała, kukurydza cukrowa, pasternak) do oczyszczania gleb skażonych kadmem, cynkiem i ołowiem. Stwierdzono, że poziom Cd, Pb i Zn malał wraz z głębokością w profilu badanej gleby. Po uprawie buraka ćwikłowego, w warstwie gleby 0-20 cm, zawartość Cd obniżyła się o 10,3%, po uprawie dyni zwyczajnej, jęczmienia i kukurydzy o 8,6%. Uprawa kapusty głowiastej białej i kukurydzy spowodowała obniżenie zawartości Cd w warstwie 20-40 cm, odpowiednio o 40,0 i 28,8%. Kapusta głowiasta biała była jednocześnie najskuteczniejsza w usuwaniu z gleby ołowiu. Po uprawie fasoli, kukurydzy i lucerny stwierdzono istotne obniżenie zawartości ołowiu w warstwach gleby 0-20 i 20-40 cm. Po uprawie dyni zwyczajnej zawartość Pb w warstwie 0-20 cm obniżyła się o 7,4%. Uprawa kapusty głowiastej białej i cykorii spowodowała obniżenie zawartości Zn w warstwie 0-20 cm odpowiednio o 21,5 i 14,1%. Opierając się na efektywności w obniżaniu zawartości metali w glebie, kukurydza i burak ćwikłowy mogą być uznane za potencjalnych remediantów w stosunku do Cd, kapusta głowiasta biała i dynia zwyczajna − Pb, a kapusta głowiasta biała − Zn.

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