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Heavy Metal Accumulation in Wild Plants: Implications for Phytoremediation

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Abstract

This work addresses the issue of Zn, Cu, Pb, Cd, Ni and Cr accumulation in wildgrown plants in the context of their possible use for the sanitation of sludge and waste substrates. The highest contents of heavy metals were noted in *Lactuca serriola, Chenopodium album, Artemisia vulgaris* and *Atriplex nitens.* Assuming maximum crop production which is to be obtained from sludge and waste substrates at a level of 2 kg d.w./m^2, it is clear that from 1 hectare several hundred grams of Pb and Cd (as well as up to 2 kg of Cu and 20 kg of Zn) may be removed.

Keywords: accumulation, heavy metals, phytoremediation.

Introduction

Phytoremediation is a method of environmental treatment that makes use of the ability of some plant species to accumulate certain elements, including heavy metals, in amounts exceeding the nutrition requirements of plants. Phytoextraction is one of the elements of phytoremediation: metals from the contaminated ground are taken up by plants and then transported from roots to shoots and removed with crops from a specified area of nature [1, 2].

Considering the possibilities for phytoremediation of waste landfill sites and areas surrounding industrial plants, important are both the ability of species to accumulate high amounts of elements per biomass unit, as well as the possibility of high biomass production over a given time and area. This is not always possible for certain plant species, even if we provide optimal growth conditions and assume that high accumulation of cadmium or lead, for example, would not reduce this growth. Therefore, despite numerous studies on plant bioaccumulators [1, 3, 4, 5, 6], it is difficult to state definitely which species could be particularly useful in environmental phytoremediation.

Plants spontaneously growing on natural and anthropogenic grounds reflect their adaptation to the given conditions of growth. Plants fixing the mobile forms of elements "clean up" the surface of the substrate while drying it up and stabilizing it. They also play the role of a protection barrier for surrounding areas [7, 8, 9]. Knowledge on the biomass element accumulation capacity which would enable the development of a treatment method for the obtained plant mass seems to be essential, as well as the assessment of the possibility of ground sanitation by plants. Plants of particular ability for the uptaking of elements from the air, water and soil and their accumulation are considered to be indicative and therefore they happen to be called bioaccumulators.

The aim of this work was to assess heavy metal accumulation in different wild plant species in the context of their usefulness in sludge and waste substrate sanitation.

Experimental Procedures

The Cu, Zn, Pb, Cd, Cr and Ni content in plants grown on sludge and waste substrates was the subject of this study. Research was carried out on sites described by Siuta and others [8-12]. Among substrates that appeared within these sites a few can be distinguished, such as: ash-sludge, waste, sludge and waste compost substrates, chemically contaminated grounds (copper smelter protection zone), as well as natural soils.

Plant species dominating the given substrates were chosen on the basis of phytosociological characteristic [13]. Samples of the whole aboveground parts of selected plant species were taken for analysis. Following mineralization of the samples in the MDS-2000 microwave digester

Table 1. Distribution of plant samples in ranges of heavy metal contents

Metal	Number of plants in heavy metal ranges in mg/kg d.w.												
	Below 1.0	1.1-2.0	2.1-3.0	3.1-5.0	5.1-10	10.1-20	20.1-50	51-100	101-200	201-300	301-500	501-1000	Above 1000
Zn					1	1	42	27	22	10	14	3	1
Cu	1	1	1	6	42	61	7	2					
Pb	74	27	11	5	3	1							
Cd	91	10	5	4	6	3	2						
Cr	41	43	14	15	3	4	1						
Ni	Below 2 mg/kg 90		16	6	7	2							

with the use of a mixture of HNO_3, HCl and HF [14], Cu, Pb, Ni, Cd, Zn and Cr contents were determined using flame AAS. Altogether, in two vegetation seasons (1997 and 1998) samples were taken from 21 different substrates and 121 plant samples were analyzed, all belonging to 42 species. Analyses were carried out in the Laboratory for Environmental Monitoring at the Institute of Environmental Protection.

Of all examined plants the following families were distinguished:

- the monocotyledons *(Graminae* sp., *Agropyron repens, Dactylis glomerata, Bromus inermis, Phleum pratense, Poa pratensis, Festuca pratensis, Festuca arundinacea, Calamagrostis epigeios, Arrhenatherum elatius, Agrostis alba, Lolium temulentium, Phalaris arundinacea, Puccinel-Ua distans, Echinochloa crus-galli);*
- the dicotyledons: the Compositae family *(Tanacetum vulgare, Lactuca serriola, Artemisia vulgaris, Rudbeckia hirta, Bidens tripartita, Tussilago farfara);* the Goose-foot family *(Atriplex nitens, Atriplex hastatum, Atriplex patula, Atriplex prostrata, Atriplex hortense, Chenopodium album, Chenopodium murale, Kochia scoparia, Kochia* sp.); the Papilionaceae family *(Trifolium re pens, Lupinus lutens);* the Polygonaceae family *(Rumex patientia, Polygonum aviculare, Polygonum nodosum);* the Cruciferae family *(Brassica campestris x B. napus, Sinapis alba, Sisymbrium loeselii);* the Crowfoot family *{Ranunculus sceleratus);* the Amaranth family *(Amaranthus retroflexus);* the Labiatae family *(Lamium album);* and the Nettle family *(Urtica dioica).*

Results

The differentiation in heavy metals content in plants is presented in Table 1. The contents of Zn range from 8 mg/kg d.w. in *Agropyron* sp. grown on a reclaimed industrial waste site to 1030 mg/kg d.w. in *Lactuca serriola* grown on a waste compost prism. It was noted that in 34% of all samples, Zn contents appeared to be within the limits of 21-50 mg/kg d.w., in 22% samples ranged between 51-100 mg/kg d.w., and in 18% - from 101 to 200 mg/kg d.w. Zn content of over 500 mg/kg d.w. was observed in *Lactuca serriola* and in *Chenopodium* sp. grown on a waste compost prism.

The contents of Cu ranged from 0.6 mg/kg d.w. in *Agropyron* sp. grown on the reclaimed industrial waste site to 80.8 mg/kg d.w. in *Artemisia* sp. grown on the waste compost prism. In most cases Cu content was within the limits of 10.1-20 mg/kg d.w. (50% of samples) and within the limits of 5.1-10 mg/kg d.w. (35% of samples). The highest Cu content was noted in *Artemisia* sp. grown on the waste compost prism and in a smelter protection zone, as well as in *Atriplex* sp. grown on an ash-sludge substrate.

Pb content ranged from 0.5 to 17 mg/kg d.w., the highest accumulation level was observed in *Artemisia* sp. and *Chenopodium* sp. grown in the smelter's protection zone, a high content of Pb was also noted in *Polygonum* sp. and *Lamium* sp. grown on the waste compost prism. For the majority of plants (83% samples) the Pb contents was lower than 2 mg/kg.

Cd content in plants ranged from 0.02 to 36.4 mg/kg d.w., the highest content of this element was noted in *Artemisia* sp., *Lactuca serriola* and *Echinochloa* sp. growing on sludge substrates. The Cd content in 75% of all samples did not exceed 1 mg/kg d.w.

No high Cr content was noted in the examined plants, the value of 1-2 mg/kg d.w. appeared most often. The highest accumulation level of this element was noted in *Lupinus* sp. (21 mg/kg) and in *Ranunculus* sp. (14 mg/kg) from the ash-sludge substrate.

The contents of Ni in the plants oscillated between 0 and 17 mg/kg d.w., the highest accumulation level was noted in *Echinochloa* sp. and *Sisymbrium* sp. grown on the sludge substrate.

The content of elements in the biomass depends mainly on the amount of mineral constituents present in the soil in the form that is available to plants, as well as on the type of the species and the development phase of the plant. The differentiation in the heavy metal content determined by growth conditions was investigated on the example of several species grown on different substrates (i.e. *Artemisia vulgaris, Lactuca serriola, Atriplex nitens, Chenopodium album* and *Agropyron repens).*

Artemisia vulgaris. The analysis was carried out on the species grown on municipal landfill, waste compost prism, reclaimed industrial waste sites, sludge substrates and grounds contaminated by the copper smelter. The Zn and Cu content was highest in *Artemisia* sp. from the waste compost prism, the Pb maximum content - in *Artemisia* sp. grown in the copper smelter protection zone, Cd and Ni maximum content — in *Artemisia* sp. from the sludge lagoon. A high accumulation of Zn, compared to plants from other substrates, was also noted in *Artemisia* sp. grown on the sludge lagoon and on the paper plant waste site. Significant amounts of Cu are accumulated also by *Artemisia* sp. grown in the smelter protection zone and on the sludge lagoon (Fig. 1).

Lactuca serriola. Analysis was carried out on *Lactuca serriola* grown on the ash- sludge substrate, waste compost prism, lagoons and sludge substrates. The contents of heavy metals differed to a great extent, e.g. the Zn content ranged from 26 mg/kg d.w. in *Lactuca serriola* from the sludge lagoon, to 1030 mg/kg d.w. in *Lactuca serriola* from the waste compost prism. The *Lactuca serriola* grown on the compost prism marks out also the highest Cu and Pb content, but *Lactuca serriola* from the sludge substrate and lagoon at Hajdow shows a significantly higher Cd and Ni content compared to *Lactuca serriola* from other substrates (Fig- 2).

Atriplex nitens. This analysis was performed on *Atriplex nitens* grown on the ash-sludge, sludge substrates and lagoon, and also on the waste compost prism and waste disposal sites. The most differing was Zn content (from 50 to 431 mg/kg d.w.) and Cu content (from 10 to 43 mg/kg d.w.). The highest Zn accumulation was noted in the *Atriplex nitens* grown on the waste compost prism and for Cu - in *Atriplex nitens* from the ash-sludge substrate (Fig. 3). The levels of other heavy metals were low.

Chenopodium album. The contents of metals in *Chenopodium album* grown on the sludge and waste substrates, the waste compost prism and the smelter protection zone varied to a significant extent. The highest Zn accumulation was observed in *Chenopodium* album from the waste compost prism, for Cu and Pb - in *Chenopodium album* from the surroundings of the smelter, Cd and Ni - in *Chenopodium album* from the sludge substrate, and Cr - in *Chenopodium album* from the municipal landfill site (Fig. 4).

Agropyron repens. The contents of heavy metals in *Agropyron repens* grown on ash-sludge, waste and sludge substrates are not high. The highest Zn content was observed in *Agropyron repens* from the sludge substrate, whereas maximum Cr content - in *Agropyron* grown on the ash-sludge substrate and on the natural soil in comparison with *Agropyron* from other substrates. The Cu, Pb and Cd contents were low in all plants (Fig. 5).

Discussion

For the phytoremediation of contaminated soils with heavy metals, plants representing high metal accumulation properties, high biomass production, and also a high level of metal transportation from the root to the shoot appear to be useful for giving the highest possible heavy metal removal from the soil. Knowledge regarding the potential ability of plant mineral element uptake and their accumulation in the biomass is not sufficient, despite many studies on heavy metal content in different plants. The chemical composition of wild plants was the subject of research performed by Siuta and Żukowska-Wieszczek [7]. These authors stated, *inter alia,* that expansive ruderal species most often present very high tolerance to heavy metals.

Kabata-Pendias and Pendias [15] reported the following toxic (excessive) metal contents in the foliage of plants of moderate tolerances to their surplus amounts: Cd 5-30, Cr 5-20, Cu 20-100, Ni 10-100, Pb 30-300 and Zn 100-4000 mg/kg d.w. Taking into consideration in this context the accumulation of metals in plants it can be stated that the toxic Cd content (over 5 mg/kg d.w.) appears in 9% of samples, mainly grown on the sludge substrate {*Artemisia* sp., *Lactuca serriola, Chenopodium* sp., *Polygonum* sp. and *Festuca* sp.). The toxic Cr content (exceeding 5 mg/kg d.w.) was noted in 7% samples, *inter alia,* in *Ranunculus* sp. and *Agropyron* sp. from the ash-sludge substrate, in *Chenopodium* sp. from the municipal landfill site and *Amaranthus* sp. from the waste compost prism.

Excessive Cu content (over 20 mg/kg d.w.) was observed in 7% samples, that is in *Artemisia* sp. and *Chenopodium* sp. grown in the smelter's protection zone, in *Atriplex* sp. from the ash-sludge substrate, in *Artemisia* sp. from the sludge lagoon and paper plant waste site, in *Artemisia* sp. and *Lamium* sp. from the waste compost prism and in *Bidens* sp. from the municipal landfill site. Excessive Ni content (over 10 mg/kg d.w.) was found only in 2 plants grown on the sludge lagoon (in *Sisymbrium* sp. and in *Graminae* sp.). The excessive Zn content (over 100 mg/kg d.w.) was noted in over 41% of samples, *inter alia,* in all plants from the waste compost prism, as well as in the majority of plants from the sludge substrates. No toxic Pb content (over 30 mg/kg d.w.) was found in the examined plants.

The very first plant for which the ability to accumulate high levels of Ni without adverse effects to its growth was observed was *Alyssum bertolonii* from the Cruciferae family. *Salix* sp., for example, is considered to be a good phytoremediator owing to its high heavy metal accumulation (especially Zn and Cd) and transportation ability, as well as high biomass production [6]. Other plants described in literature [1-5, 16-18], that accumulate high amounts of metals belong to the Cruciferae family and are as follows: *Thlaspi caerulescens, Brassica nigra,* and *Brassica juncea.* For example, the Pb content obtained in model experiments in the dry weight of *Brassica pekinensis* was on the level of 3.4% [18], and in *Thlaspi caerulescens* Zn content was 2.6% [4]. However, verifying the obtained model study results in field studies is difficult because many metals in the soil appear in forms unavailable to plants, as opposed to water cultures, where metals are assimilated by plants.

Element concentration per mass unit presents one of the distictive features (characteristics) applied for the assessment of the possible use of the species in environmental phytoremediation, with another being the biomass production level obtained from a given area and within a given period of time. Studies on the possibilities of the use of plants in the remediation most often report only the metal contents in different plant species, but they seldom provide information on the crop production level obtained in certain conditions. However, the collected results from literature [6, 19, 20] enabled the calculation of estimated Cd, Zn and Pb removal per 1 hectare with the plant biomass obtained in field studies (Tab. 2).

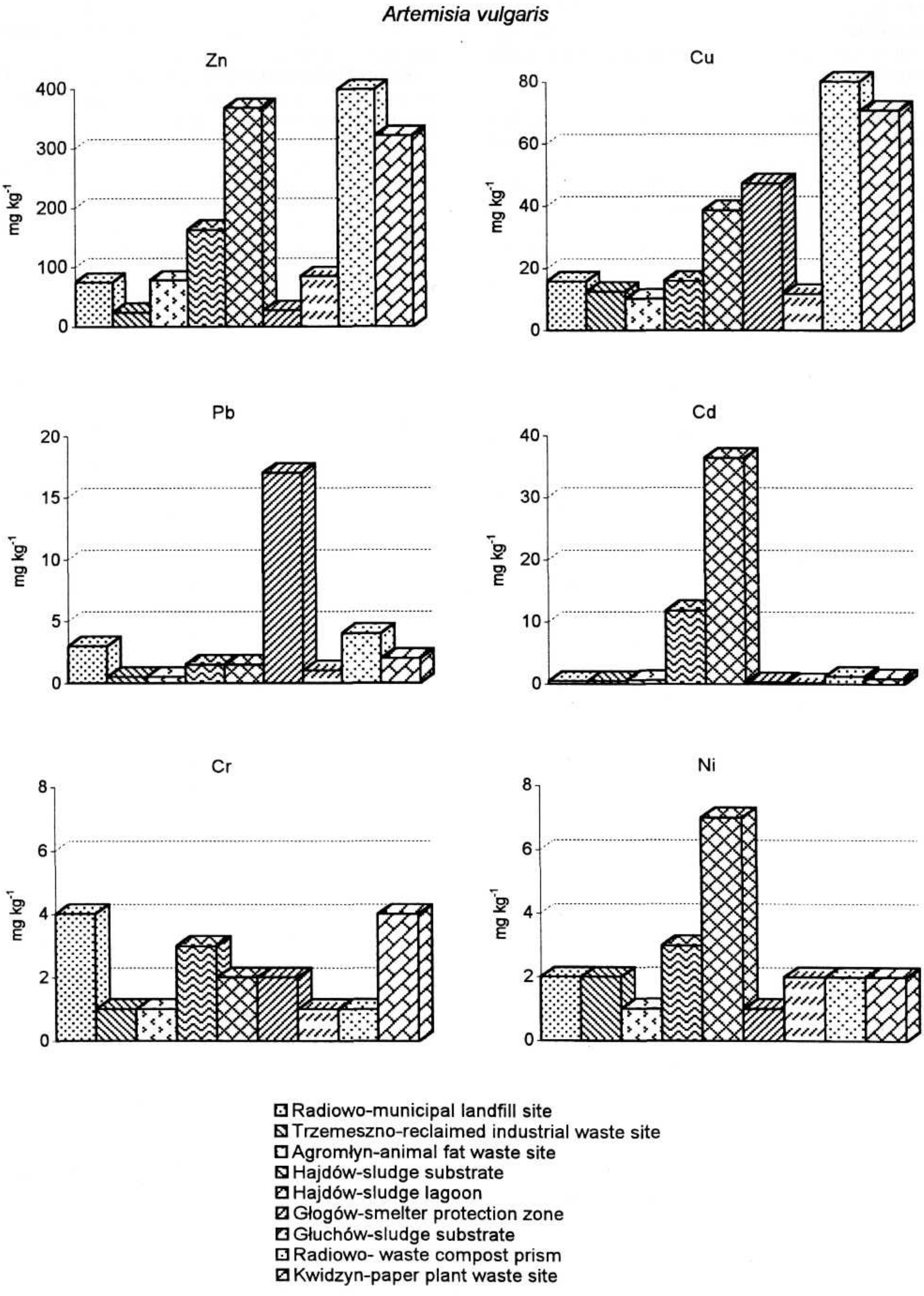

Fig. 1. Heavy metals content in *Artemisia vulgaris* grown on different substrates.

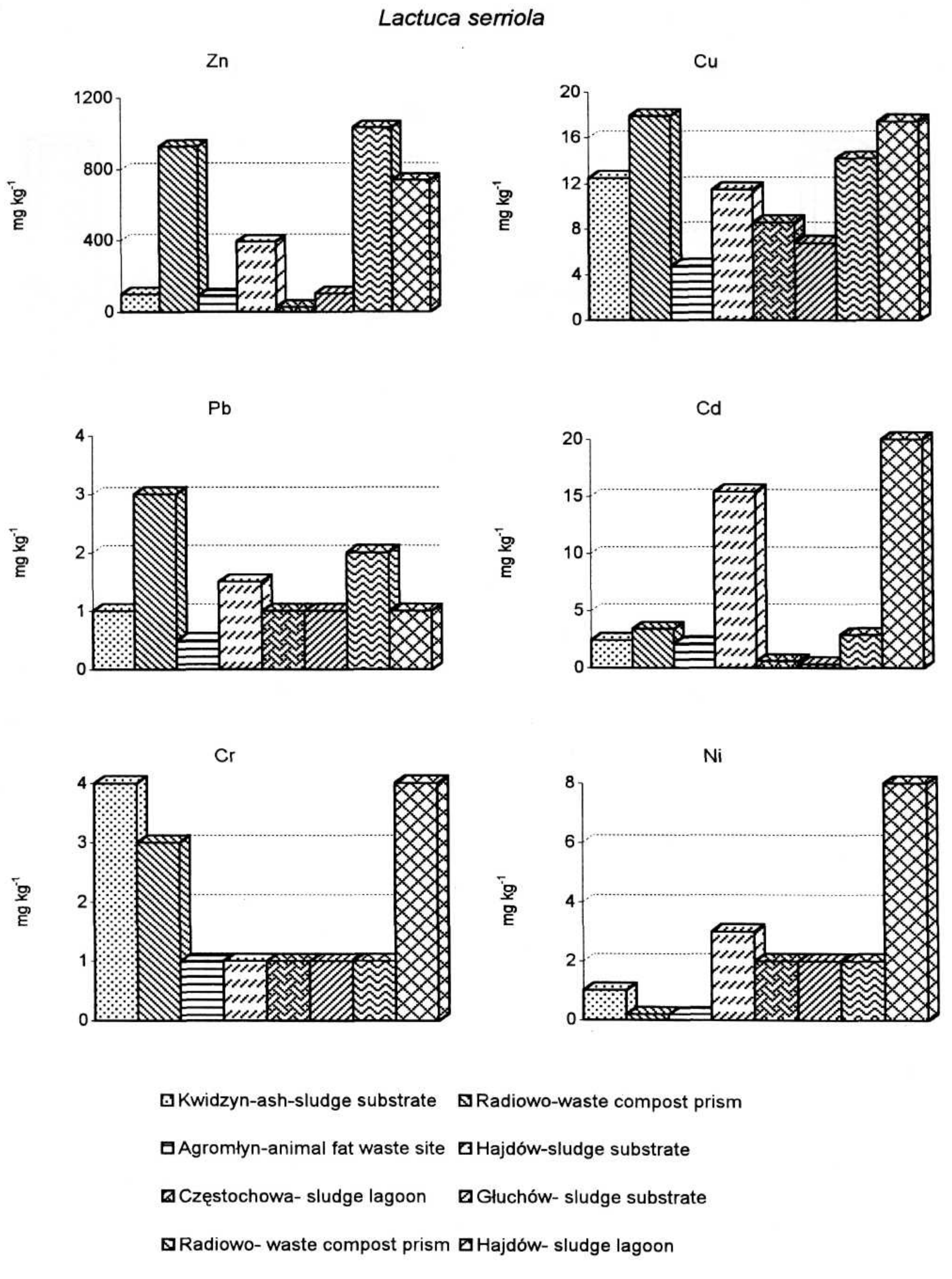

Fig. 2. Heavy metals content in *Lactuca serriola* grown on different substrates.

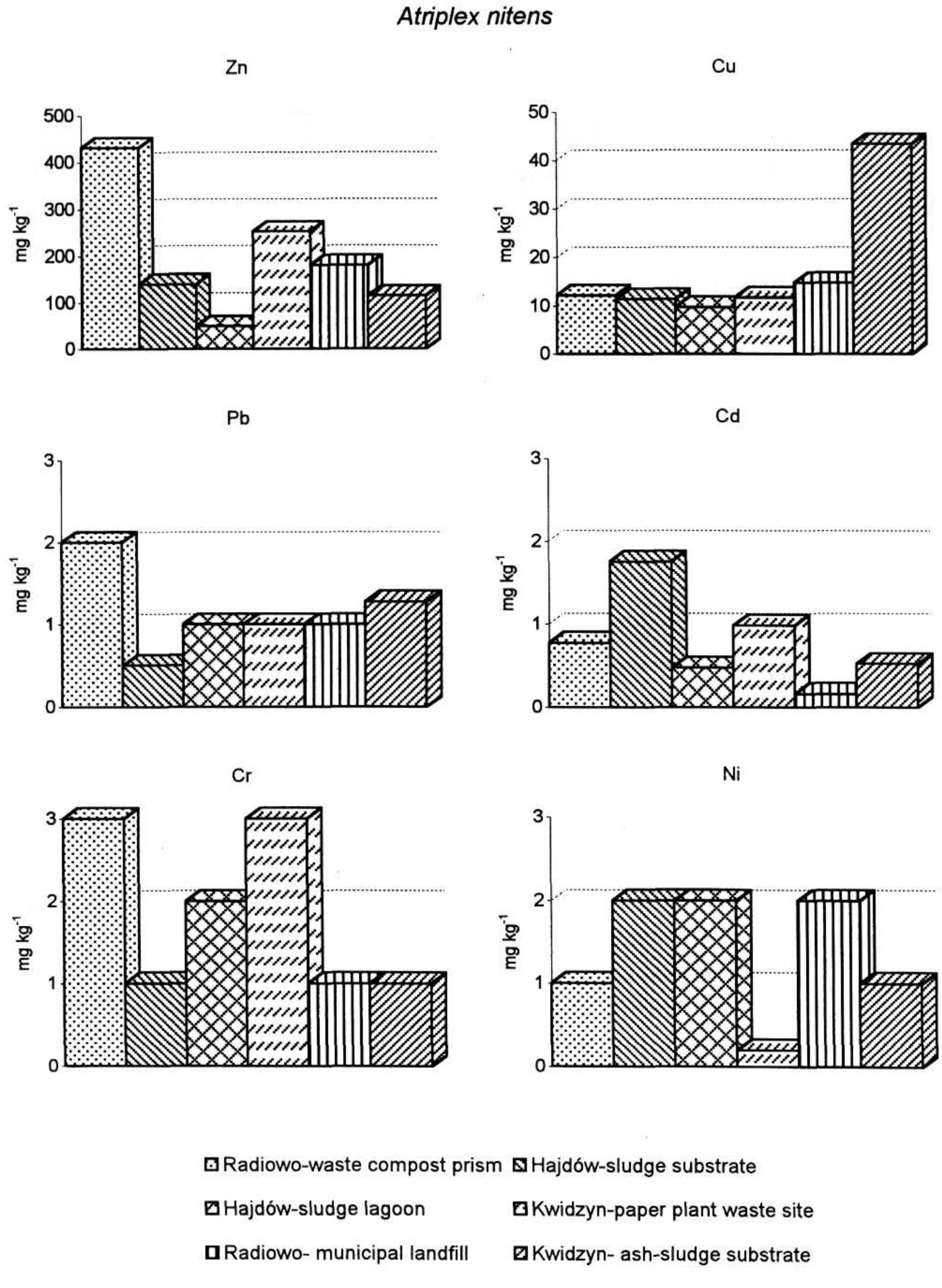

Fig. 3. Heavy metals content in *Atriplex nitens* grown on different substrates.

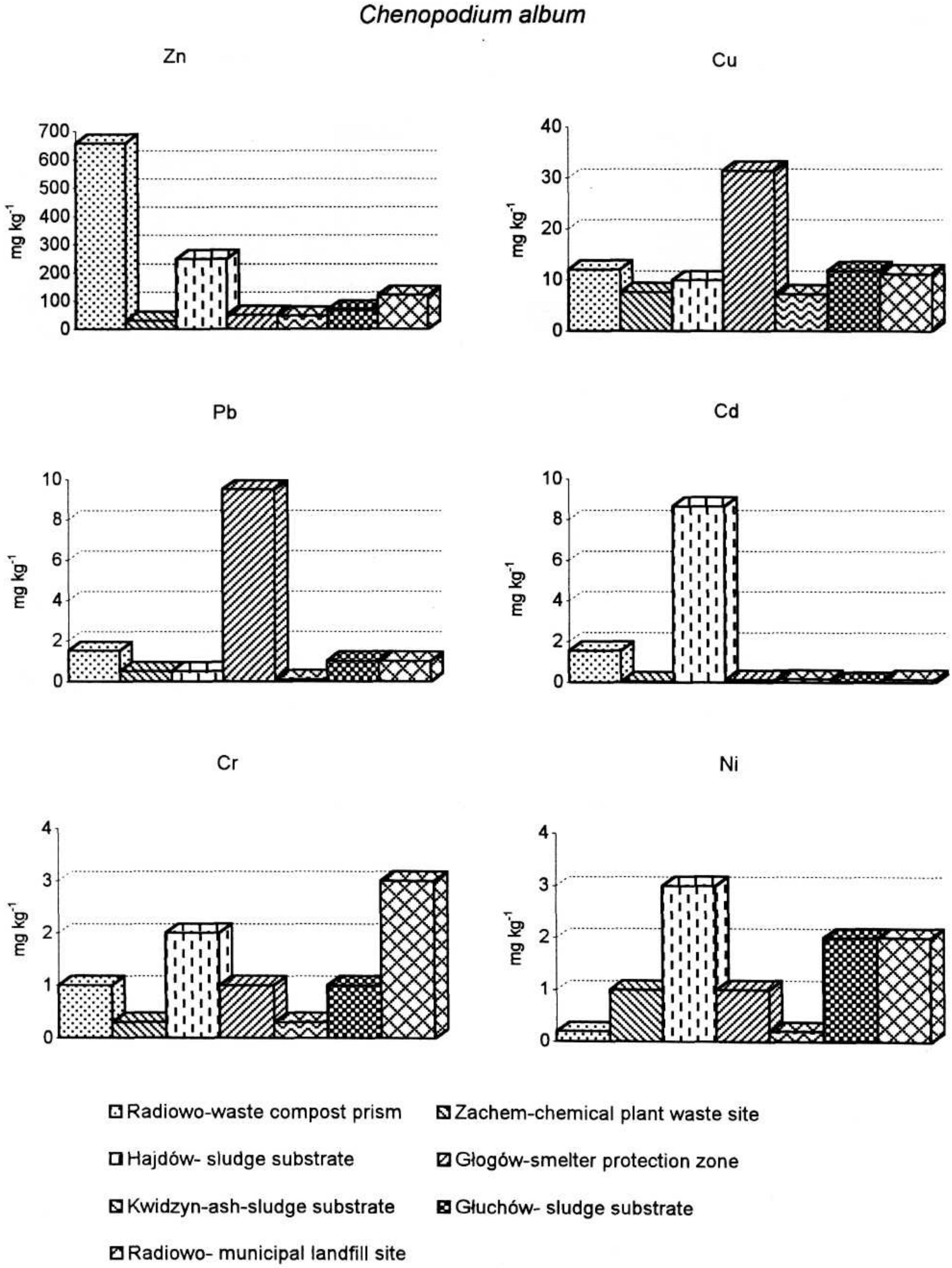

Fig. 4. Heavy metals content in *Chenopodium album* grown on different substrates.

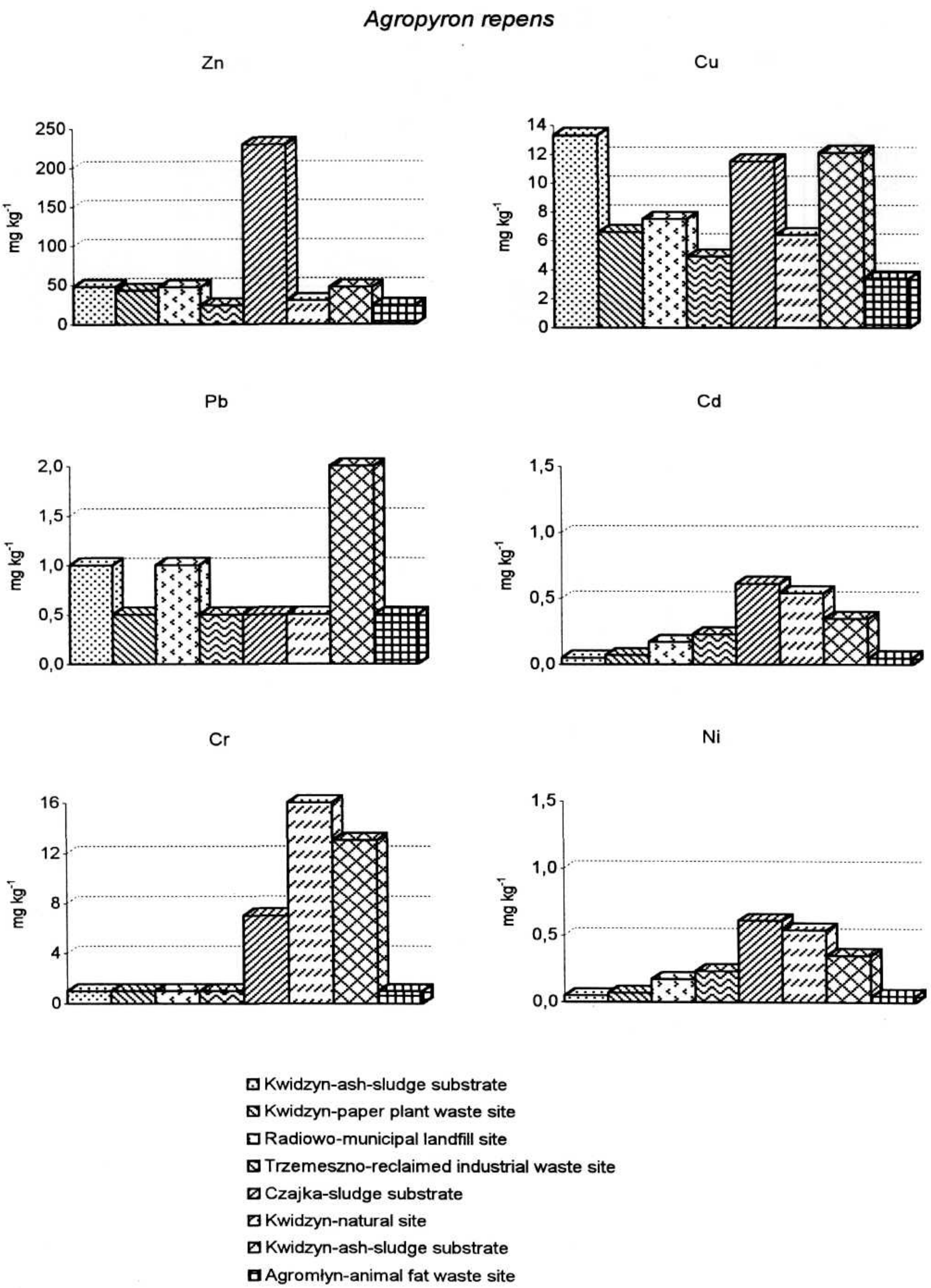

Fig. 5. Heavy metals content in *Agropyron repens* grown on different substrates.

Table 2. Estimated removal of Cd, Zn and Pb with the biomass.

Plant	Biomass (t/ha)	Metal contents (mg/kg d.w.)	Metal removal (g/ha)	Reference
Cd				
Thlaspi caerulescens	2.93	12.1	35	[9]
Alyssum murale	1.32	33.7	43	[9]
Salix viminalis	10.0	22.1	217	[9]
Potato – tuber	14.77	3.2	47	[18]
Barley – straw	4.95	2.4	12	[18]
Barley – grain	3.14	0.70	2	[18]
White clover	3.52	1.14	4	[18]
Zn				
Maize	9.4	79.3	745	[19]
Maize	3.52	113	398	[18]
Potato – tuber	14.77	172	2540	[18]
Barley – grain	3.14	58	182	[18]
Barley – straw	4.95	99	490	[18]
Pb				
Maize	9.4	2.07	19	[19]
White clover	3.52	7.8	27	[18]
Potato – tuber	14.77	15.4	227	[18]
Barley – grain	3.14	2.2	7	[18]
Barley – straw	4.95	13	64	[18]

Table 3. Estimated removal of Zn, Cu, Pb and Cd with the mass of plants grown on sludge and waste substrates.

Metal	Plant	Metal content (mg/kg d.w.)	Metal removal (g/ha)
Zn	*Lactuca serriola*	1030	20600
	Chenopodium album	658	13200
	Atriplex nitens	431	8600
	Artemisia vulgaris	398	8000
Cu	*Artemisia vulgaris*	81	1620
	Atriplex nitens	43	860
	Chenopodium album	31	620
Pb	*Artemisia vulgaris*	17	340
	Chenopodium album	10	200
Cd	*Artemisia vulgaris*	36	720
	Lactuca serriola	21	420
	Echinochloa crus-galli	16	320

Plant growth on sludge, waste compost and waste substrates appears to be very luxuriant, the vegetation covering the surface with a dense compact layer [7, 9, 13, 21]. The populations of the observed different species reach two (or sometimes three) times the level given as diagnosis features in keys for determining species. Of the wild plants (*Artemisia* sp., *Lactuca serriola*, *Rudbeckia* sp., *Bidens* sp., *Tanacetum* sp., *Atriplex* sp., *Chenopodium* sp., *Ranunculus* sp., *Solanum* sp., *Graminae* sp.) grown on substrates contaminated with heavy metals, the highest metal content was noted in *Lactuca serriola, Chenopodium* sp., *Artemisia* sp. and *Atriplex* sp. For example, in *Artemisia vulgaris* the Cd concentration in the dry weight was as high as 37 mg/kg, Cu - up to 81 mg/kg, Zn - up to 400 mg/kg, whereas in *Chenopodium album:* 9 mg Cd/kg, 31 mg Cu/kg and 660 mg Zn/kg. The highest Pb concentration was noted in *Artemisia vulgaris* (17 mg/kg d.w.), whereas the highest Zn concentration (1030 mg/kg d.w.) - in *Lactuca serriola* (Tab. 3).

Assuming that 2 kg d.w./m^2 is the maximum crop production level to be achieved from sludge and waste substrates rich in elements available to plants, it seems possible to remove a few hundreds of grams of Pb and Cd, up to 2 kg of Cu and even 20 kg of Zn from the area of 1 hectare (Tab. 3). The above estimation presents a certain approximation; however, studies destined to determine the crop production level of plants grown on 1 m^2 area, carried out on three different substrates, provided results within the limits of 1.5-1.8 kg of dry weight.

Comparing data from literature and our own research (Tables 2, 3) it appears that wild plants may be better phytoremediators, especially for waste and sludge substrates, than the metal bioaccumulators known from literature (*Thlaspi* sp., *Alyssum* sp., *Salix* sp.). It has been observed that all plant species grown on anthropogenic substrates rich in organic matter show a distinctive luxuriant growth, and the study results indicate high concentrations of all elements in the biomass [13, 21]. At the same time it should be noted that the accumulation of heavy metals (mainly Zn and Cu), only in a small number of samples exceeded the safe values in terms of biomass use, e.g. as animal feed. This suggests that the biomass from anthropogenic substrates may be used, after having been composted with substances poor in mineral elements (e.g. sawdust, straw), for fertilizing urban green areas and reclaimed lands.

Comparing the amount of elements that can be taken up by plants from the given growth substrate with their total contents in this substrate it appears that, generally, it is a very small value, possibly significantly smaller than 1%. In other words, site sanitation in terms of element removal with plant crops may take well over twenty years. Nevertheless, due to the fact that plant growth is determined by the amount of elements in soluble form, even after one vegetation period the loss of elements available to plants is significant. Furthermore, the reduction of the amounts of mobile forms of elements reduces the possibility of them being washed out from the substrate and transported to ground waters.

The study results presented here indicate that the scale of possibilities for environmental treatment, *inter alia*, leading to the reduction of heavy metal content, varies and it depends on both the properties of the species, as well as growth conditions. We have to be aware of the fact that despite using species accumulating high amounts of different heavy metals per mass unit, and creating them best possible growth conditions, we end up with quite a low level of heavy metal removal with the phytomass from a given substrate. Nevertheless, vegetation cover is of great significance in the remediation of contaminated grounds because it stabilizes and dries them up, initiates biological processes, and also creates a protection barrier for the adjacent areas.

In summary up it can be stated that metal removal from sludge and waste substrates is most effective with the use of *Lactuca serriola, Artemisia vulgaris, Chenopodium album* and *Atriplex nitens.*

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