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EFFECT OF SEWAGE SLUDGE IN SOIL ON Cd, Pb AND Zn ACCUMULATION IN THE *Linum usitatissimum* L.

WPŁYW OSADÓW ŚCIEKOWYCH W GLEBIE NA AKUMULACJĘ Cd, Pb ORAZ Zn W *Linum usitatissimum* L.

Abstract: Sewage sludge is the product of the process of wastewater treatment. Sludge may be considered hazardous waste requiring costly disposal procedures, or may be perceived as a source of nutrients for use on agricultural land. Experiments were carried out in simulated natural conditions in pots set in the land to a depth of 50 cm with variations of graded mixture of natural sediments and soils. Sewage sludge sedimentation was added into the weighed quantity of soil in the proportions: sludge – soil = 1:2 (var. K1), 1:3 (var. K2), 1:4 (var. K3), 1:5 (var. K4), 1:6 (var. K5). Control variant (K0) without the presence of sewage sludge has also been sown with all varieties. Studied crop were the varieties of flax and linseed. Flax and linseed varieties variously accumulated particular metallic elements, the highest concentrations were recorded for Zn, followed by the Pb and Cd. The lowest concentrations of Cd and Pb were analyzed in the seed (0.121 $mg \cdot kg^{-1}$) and the highest concentrations of Cd and Pb were detected in the stem (Cd = 0.396 $mg \cdot kg^{-1}$) and capsules (Pb = 1.881 $mg \cdot kg^{-1}$). The highest concentration of Zn was found in the capsule (115.015 $mg \cdot kg^{-1}$) and lowest in the root (33.782 $mg \cdot kg^{-1}$). Trend of accumulation of Cd was: stem > capsule > root > seed, Pb: capsule > stem > root > seed, Zn: capsule > seed > root > stem. The results of studied experiments show that the particular varieties of fiber and linseed have different variability in the ability to draw heavy metals from the soil and consequently different phytoremediation potential.

Keywords: *Linum usitatissimum* L., flax, linseed, cadmium, lead, zinc

Sewage sludge is the product of the process of wastewater treatment. Sludge may be considered hazardous waste requiring costly disposal procedures, or may be perceived as a source of nutrients for use on agricultural land. For application of sewage sludge on agricultural land at the Czech Republic the concentration limits of chosen risk elements

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have to be respected and the only these sewage sludges which are in the agreement with the respective regulationare allowed to be used. Limit (maximum) concentrations in sludge are for Cd 5 mg · kg^{-1}, Cu 500 mg · kg^{-1}, Pb 200 mg · kg^{-1}, Zn 2500 mg · kg^{-1}, As 30 mg · kg^{-1}, Cr 200 mg · kg^{-1} and Ni 100 mg · kg^{-1} d.m. Bioavailability of heavy metals is not directly correlated with their total concentrations in soil or sludge. Availability of heavy metals from sewage sludge to the plants is mainly determined by soil properties. Mobility of metals in the soil after application of sewage sludge depends mainly on chemical and physical properties of sludge – soil. Metals originated from sewage sludge are mainly accumulated in the surface layers of soil and Zn is the most accessible for the organisms. Sewage sludges contains high levels of organic and inorganic nutrients, but the availability of toxic metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) in cultivated crops [1, 2] is considered to be the main problem. Knowledge of the crops characteristics on contaminated sites and their potential ability to transfer metal contaminants in the harvested plant parts can be a very important finding for future phytoremediation applications. Studies in the plants [3] for the ability to accumulate Cd, Pb and Zn in soil enriched sewage sludge showed differences between crops and their varieties.

Materials and methods

The experiment was conducted at the agricultural research institute Agritec, Ltd. of Sumperk, located in the middle Europe in the North Moravia part of the Czech Republic at $49^{o}58'21.213''$N latitude, $16^{o}58'0.341''$E, longitude and 329 m above the sea level. The experiment was conducted during the growing season April–August 2005, 2006 and 2007. This growing periods of the years were characterized by average monthly temperatures between 8.3 ^{o}C and 20.5 ^{o}C. Average monthly maximal temperatures fluctuated between 20.4 and 35.2 and the average monthly minimal temperatures between –6.0 ^{o}C and 8.0 ^{o}C. The total rainfall was 297.5 mm in 2005, 365.7 mm in 2006 and 247.5 mm in 2007, respectively compared with long-term average rainfall 339.5 mm in the monitored growing periods. Experiments were carried out in simulated natural conditions in pots set in the land to a depth of 50 cm with variations of graded mixture of natural sediments and soils. Sewage sludge sedimentation was added into the weighted quantity of soil in the proportions: sludge – soil = 1:2 (var. K1), 1:3 (var. K2), 1:4 (var. K3), 1:5 (var. K4), 1:6 (var. K5). Control variant (K0) without the presence of sewage sludge has also been sown with all varieties. Jitka, Laura, Viola, Mercury, Venica, Hermes, Jordan, Escalina, Viking, Tabor, Bonet, Agatha, Super, Marylin, Ilona, Elektra, Atalante, Flanders, Lola and Biltstar were the studied flax and linseed varieties. Harvested plants were dried, separated into the stem, capsules, root and seed and analyzed.

Table 1

Chemical characterization of natural soil used in the experiments

	pH/$CaCl_2$	K	P	Mg	Ca	N-NH_4	N-NO_3	Cd	Pb	Zn
mg · kg^{-1} d.m.	6.75	171	73	201	2047	3.89	6.5	0.25	32.8	56.4

Table 2

Chemical characterization of used sewage sludge

	mg · kg^{-1} d.m.								%	mg · kg^{-1} d.m.		g · kg^{-1} d.m.			
pH	Pb	Cd	Cu	Zn	Cr	Ni	As	Hg	N total	N-NH_4	N-NO_3	P total	Ca	Mg	K
8.05	57.6	1.7	198	1250	155	28.1	4.3	1.9	4.8	9410	49.9	28	33.3	6.27	5.05

The digestion of plant materials was performed in a microwave oven operating system (Milestone, ETHOS D) with an energy output 0–400 W (0–100 % potency, respectively). Approximately 0.5 g of dry plant materials were placed into the teflon microwave digestion vessels, then 5 cm^3 of 65 % HNO_3 and 1 cm^3 of 30 % H_2O_2 were added to each sample. Plant samples were digested using the optimatized microwave programs. After cooling to room temperature the digested samples were diluted to a final volume of 25 cm^3 with deionized water. Blank samples were prepared simultaneously. These solutions were stored in a refrigerator at 4 ^{o}C until the analysis was carried out. The total contents of elements (Cd and Pb) in the digests were determined by graphite furnace atomic absorption spectroscopy (SOLLAR M, Unicam Ltd., Cambridge, U.K.) equipped with Zeeman and deuterium background correctors, a graphite furnace GF95 and an auto-sampler. For the determination of Zn there was used flame atomic absorption spectroscopy. For this work, the deuterium lamp was used as background corrector for determination of Zn and Cd, the Zeeman corrector was employed for determination of Pb. The wavelengths used for quantification were: λ = Cd 228.8 nm; Pb 217.0 nm and Zn 213.9 nm. Certified reference materials IRM 9035 kohlrabi-haulm ÚKZÚZ Brno were applied for quality assurance of analytical data**.** The results data were statistically analyzed by using the statistical package program Statistica, using analysis of variance and multiple comparisons and correlation.

Results and conclusions

The highest concentration was found in zinc (15.51–375.2 mg · kg^{-1} d.m.), followed by lead (Pb) with (0.01–5.85 mg · kg^{-1} d.m.) and the lowest concentration was detected in cadmium (0.007–5.22 mg · kg^{-1} d.m.). Individual studied metals were variously accumulated into organs of flax and linseed. The application of sewage sludge influenced the level of Cd content in all flax organs. Lead and zinc content in flax and linseed plants fluctuated in the respective variants and did not show signifiant increasing tendency in all organs by the increasing content of sewage sludge into the soil similarly as Balik et al [4] investigated by Zn accumulation in oat. By mutual evaluation of concentration of heavy metals in different organs the highest accumulation of cadmium was found in stem, lead (Pb) and zinc in capsules. On the contrary, the lowest concentration of cadmium and lead (Pb) was detected in seed and the lowest concentration of zinc was found in root. Cadmium was more accumulated by linseed varieties, whereas lead (Pb) and zinc were more accumulated by flax varieties. Variant with the highest sewage sludge content 1K significantly ($p \geq 0.05$) concentrated

Table 3

Heavy metal (Cd, Pb and Zn) uptake/accumulation (mg Cd, Pb, Zn · kg^{-1} d.m.; g Cd, Pb, Zn · ha^{-1}) by organs of flax and linseed plants from sewage sludge-amended soil irrespective of tested cultivars (data for 20 flax and linseed cvs.). Analysis of variance; mature plants; field-simulated experiment 2005–2007

	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
	mg Cd · kg^{-1}				g Cd · ha^{-1}			
1K = 1:2	0.376^{b}	0.566^{c}	0.535^{c}	0.164^{e}	0.420^{b}	3.972^{b}	0.428^{c}	0.147^{c}
2K = 1:3	0.323^{a}	0.444^{bc}	0.514^{bc}	0.154^{de}	0.312^{a}	2.489^{a}	0.414^{c}	0.166^{c}
3K = 1:4	0.313^{a}	0.375^{ab}	0.409^{b}	0.128^{cd}	0.297^{a}	1.960^{a}	0.321^{b}	0.130^{bc}
4K = 1:5	0.309^{a}	0.335^{ab}	0.285^{a}	0.111^{bc}	0.288^{a}	1.560^{a}	0.216^{a}	0.123^{bc}
5K = 1:6	0.302^{a}	0.296^{a}	0.265^{a}	0.092^{ab}	0.312^{a}	1.447^{a}	0.220^{a}	0.088^{ab}
Control	0.298^{a}	0.362^{ab}	0.263^{a}	0.074^{a}	0.279^{a}	1.627^{a}	0.224^{a}	0.056^{a}
	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
	mg Pb · kg^{-1}				g Pb · ha^{-1}			
1K = 1:2	1.135^{a}	0.929^{ab}	1.699^{a}	0.573^{b}	1.247^{bc}	6.065^{b}	1.469^{a}	0.606^{b}
2K = 1:3	1.045^{a}	0.886^{ab}	1.716^{ab}	0.657^{b}	0.984^{ab}	4.082^{a}	1.345^{a}	0.785^{b}
3K = 1:4	1.037^{a}	0.887^{ab}	1.713^{ab}	0.612^{b}	0.911^{a}	3.864^{a}	1.399^{a}	0.685^{b}
4K = 1:5	1.067^{a}	0.832^{ab}	1.982^{b}	0.593^{b}	0.954^{ab}	3.312^{a}	1.526^{a}	0.695^{b}
5K = 1:6	1.103^{a}	0.748^{a}	2.271^{c}	0.547^{b}	1.009^{ab}	3.408^{a}	1.860^{b}	0.655^{b}
Control	1.574^{b}	0.901^{b}	1.907^{ab}	0.328^{a}	1.480^{c}	3.587^{a}	1.645^{ab}	0.237^{a}
	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
	mg Zn · kg^{-1}				g Zn · ha^{-1}			
1K = 1:2	37.893^{b}	39.085^{c}	117.638^{a}	74.811^{b}	37.753^{b}	201.409^{b}	95.831^{a}	70.388^{b}
2K = 1:3	36.266^{b}	35.804^{ab}	112.596^{a}	74.131^{b}	31.369a	169.973^{ab}	91.689^{a}	69.161^{b}
3K = 1:4	36.321^{b}	36.389^{bc}	109.012^{a}	74.229^{b}	30.925a	159.728^{a}	87.910^{a}	67.894^{b}
4K = 1:5	32.193^{a}	34.010^{ab}	116.041^{a}	70.867^{b}	28.795a	139.656^{a}	91.797^{a}	65.107^{b}
5K = 1:6	30.925^{a}	32.759^{a}	116.468^{a}	71.595^{b}	29.846a	151.355^{a}	101.151^{a}	68.433^{b}
Control	29.092^{a}	46.713^{d}	118.333^{a}	61.426^{a}	27.559a	200.091^{b}	99.684^{a}	42.769^{a}

Table 4

Correlation HMs between individual plant organs

	Cd				Pb				Zn			
	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
Root		0.41	–0.01	0.13		–0.07	0.06	–0.46		0.32	0.41	–0.04
Stem	0.41		0.15	0.12	–0.07		0.27	0.09	0.32		0.40	–0.26
Capsule	–0.01	0.15		0.23	0.06	0.27		–0.18	0.41	0.40		–0.23
Seed	0.13	0.12	0.23		–0.46	0.09	–0.18		–0.04	–0.26	–0.23	

cadmium into all organs in contrary to control variant of Table 8. The found Cd concentration indicates trend of accumulation in the direction of stem > capsule > root > seed, similarly to work Jiao et al [5], who found decreasing direction of accumulation at harvest time: stem>seed. The trend of lead (Pb) transport was following: capsules > stem > root > seed. The concentration of lead (Pb) in root was equal in all variants enriched by sludge. However, it was significantly ($p \geq 0.05$) lower in comparison with the control. On the other hand, the concentration of lead (Pb) in a seed had completely opposite tendency and varied in stem and capsules. The trend of zinc concentration was: capsule > seed > root > stem and the highest was in the capsule, but between the individual variant was balanced and insignificantly higher in the control variant. The zinc content in a stem was different in individual variants with significantly highest content of the control. Zinc accumulated in root shows significant ($p \geq 0.05$) influence on variants with higher content of sludge (Table 3). While studying concentration of zinc in a seed there was found significantly ($p \geq 0.05$) increasing content of element with increasimg amount of sludge in soil. Table 3 represents total accumulation of heavy metals, so-called absorption factor, that is absorption of risk element by crop per area unit ($g \cdot ha^{-1}$). By biomass of above-ground mass, on contrary of total crop mass, was absorbed off 89 % Cd, 85 % Pb and 91 % Zn. Stem had the highest absorption factor of all three elements (mean 2.176 $g\ Cd \cdot ha^{-1}$, 4.053 $g\ Pb \cdot ha^{-1}$ a 170.369 g $Zn \cdot ha^{-1)}$. Cd absorption was higher in linseed varieties (except of root), in contrary to Pb and Zn absorption was higher from flax (except of capsules and seeds). These trends of absorption by individual organs of flax and linseed plants were found out from resultant analyses of gained data: Cd = stem > root > capsule > seed, Pb = stem > capsule > root > seed, Zn = stem > capsule > seed > root. Absorption of Cd by all parts of plant was significant ($p \geq 0.05$) for variants with higher content of sludge in soil. Absorption of Pb was above all significant ($p \geq 0.05$) for variant 1 K and absorption of Zn was after application of sewage sludge significant only for root, stem and seed also in variant 1K. When studying extract of cadmium from soil substrate and sewage sludge Piotrowska and Cyplik et al [5] came to similar conclusions. They learned increased content of Cd in root. By mutual evaluation of accumulation of monitored heavy metals there was found correlative dependence of Cd accumulation into stem and root ($r = 0.414$) and correlation in accumulation Pb bettwen roots and stem ($r = -0.456$) and stem and capsules ($r = 0.411$), see Table 4. The results show, that individual varieties of flax and linseed have different variability in ability to accumulate heavy metals from soil. Variety of linseed Flanders showed the highest concentration of Cd in root, capsules and seed (Table 5). This variety had significantly ($p \geq 0.05$) higher concentration Pb in seed. In variety of flax Jitka was found the highest concentration of Pb in stem and capsules (Table 6). An interesting fact was, that the highest concentrations of Zn were always found in flax varieties (root – Viola, stem – Marylin, capsule – Hermes, seed – Jordán) (Table 7), but by mathematics analyses of calculation of absorption factor, the highest found absorption in root and stem was by variety of flax Jordan (root: 40.191 $g \cdot ha^{-1}$, stem: 238.298 $g \cdot ha^{-1}$), but linseed Biltstar (145.187 $g \cdot ha^{-1}$) drew off more into capsules and variety linseed Atalante (105.443 $g \cdot ha^{-1}$) – seed. The variety of flax Jordan presents the highest accumulative potential of Pb in stem (5.812 $g \cdot ha^{-1}$), variety

Table 5

Cadmium uptake/accumulation (mg Cd · kg^{-1} d.m.; g Cd · ha^{-1}) by organs of flax and linseed plants from sewage sludge-amended soil irrespective of tested variant. Mean; mature plants; field-simulated experiment 2005–2007

Variety	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
	mg Cd · kg^{-1}				g Cd · ha^{-1}			
Hermes	0.338	0.320	0.446	0.103	0.396	1.828	0.271	0.089
Jitka	0.308	0.445	0.414	0.159	0.238	2.719	0.338	0.118
Venica	0.319	0.316	0.221	0.100	0.364	1.917	0.177	0.122
Merkur	0.303	0.340	0.376	0.100	0.272	1.589	0.259	0.078
Bonet	0.293	0.408	0.390	0.103	0.236	2.127	0.218	0.086
Tábor	0.347	0.449	0.394	0.111	0.314	2.629	0.295	0.110
Viola	0.369	0.368	0.276	0.096	0.310	2.218	0.198	0.075
Viking	0.359	0.352	0.417	0.095	0.378	1.888	0.366	0.082
Agatha	0.346	0.477	0.423	0.143	0.409	3.518	0.308	0.130
Escalina	0.277	0.317	0.386	0.100	0.276	1.747	0.295	0.104
Ilona	0.312	0.377	0.366	0.108	0.323	2.004	0.214	0.092
Super	0.286	0.356	0.348	0.128	0.256	1.506	0.244	0.097
Elektra	0.320	0.326	0.307	0.087	0.380	2.166	0.181	0.056
Marylin	0.366	0.417	0.434	0.121	0.425	2.257	0.368	0.115
Jordán	0.277	0.384	0.359	0.132	0.328	2.697	0.292	0.096
Laura	0.315	0.383	0.334	0.118	0.337	1.885	0.262	0.119
Atalante	0.305	0.433	0.412	0.142	0.304	2.418	0.432	0.227
Flanders	0.253	0.351	0.465	0.181	0.232	1.176	0.433	0.234
Lola	0.349	0.430	0.450	0.119	0.230	1.301	0.351	0.188
Biltstar	0.363	0.681	0.353	0.168	0.353	3.986	0.573	0.149

Table 6

Lead uptake/accumulation (mg Pb · kg^{-1} d.m.; g Pb · ha^{-1}) by organs of flax and linseed plants from sewage sludge-amended soil irrespective of tested variant. Mean; mature plants; field-simulated experiment 2005–2007

Variety	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
	mg Pb · kg^{-1}				g Pb · ha^{-1}			
Hermes	1.183	0.808	2.117	0.557	1.256	3.949	1.430	0.558
Jitka	1.073	1.087	2.343	0.600	0.892	5.679	2.029	0.491
Venica	1.184	0.855	1.609	0.556	1.239	4.725	1.336	0.791
Merkur	1.305	0.927	1.754	0.526	1.076	4.203	1.283	0.489
Bonet	0.983	0.792	1.927	0.488	0.769	3.410	1.312	0.503
Tábor	1.081	0.781	1.773	0.489	0.922	3.930	1.378	0.550
Viola	1.241	0.895	2.018	0.441	1.063	5.191	1.451	0.420
Viking	1.192	0.835	1.683	0.494	1.289	4.431	1.688	0.554
Agatha	1.075	0.889	1.595	0.551	1.265	4.997	1.260	0.577
Escalina	1.231	0.905	2.145	0.584	1.183	4.573	1.681	0.680
Ilona	1.137	0.868	2.252	0.552	0.971	4.053	1.425	0.537
Super	1.260	0.816	1.942	0.569	1.034	3.132	1.489	0.480
Elektra	1.135	0.717	1.804	0.610	1.209	3.949	1.120	0.444
Marylin	0.988	0.779	1.961	0.561	1.029	4.124	1.585	0.542
Jordán	1.172	0.961	1.989	0.551	1.341	5.812	1.508	0.399
Laura	1.022	0.958	1.782	0.546	1.046	4.329	1.496	0.663
Atalante	1.399	0.778	1.555	0.557	1.435	2.945	1.647	0.993
Flanders	1.171	0.873	1.802	0.706	1.042	2.330	1.798	1.028
Lola	1.279	0.865	1.882	0.540	0.875	2.263	1.485	0.852
Biltstar	1.089	0.888	1.690	0.558	1.015	3.038	2.414	0.662

Table 7

Zinc uptake/accumulation (mg Zn · kg^{-1} d.m.; g Zn · ha^{-1}) by organs of flax and linseed plants from sewage sludge-amended soil irrespective of tested variant. Mean; mature plants; field-simulated experiment 2005–2007

Variety	Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
	mg Zn · kg^{-1}				g Zn · ha^{-1}			
Hermes	34.294	36.921	135.152	71.530	36.526	192.214	98.000	55.428
Jitka	33.999	40.694	129.667	74.767	26.131	186.563	102.144	57.474
Venica	32.650	36.408	99.740	69.987	34.164	201.528	85.222	79.613
Merkur	35.134	37.249	106.248	67.710	27.776	139.086	79.856	50.648
Bonet	30.806	36.673	106.958	71.125	23.425	159.847	75.637	59.507
Tábor	31.629	37.803	118.981	73.572	27.314	194.948	96.153	69.966
Viola	39.568	37.117	113.759	70.604	33.161	191.841	86.379	54.142
Viking	33.834	35.481	104.983	71.288	32.062	172.937	110.961	58.642
Agatha	27.904	35.919	95.629	68.144	29.928	196.964	73.999	60.813
Escalina	38.104	37.651	115.926	66.891	34.197	171.101	87.882	66.153
Ilona	33.716	37.754	117.925	75.498	30.299	180.807	83.819	54.311
Super	33.841	33.071	113.186	72.918	27.123	127.095	86.779	50.431
Elektra	33.253	35.448	102.679	68.958	36.946	198.972	64.145	43.104
Marylin	33.567	41.392	128.114	76.284	36.403	217.994	108.826	66.334
Jordán	33.267	38.469	118.469	77.860	40.191	238.298	95.295	54.282
Laura	38.074	39.442	118.162	75.613	37.109	164.529	98.155	72.798
Atalante	31.946	34.034	102.243	70.049	29.886	130.248	100.939	105.443
Flanders	29.330	39.133	132.313	62.120	24.190	103.126	121.591	71.819
Lola	32.471	38.986	123.902	64.099	21.179	95.162	92.572	79.537
Biltstar	38.241	39.559	116.255	74.512	32.816	144.111	145.187	68.726

Table 8

Heavy metal (Cd, Pb and Zn) uptake/accumulation (mg Cd, Pb, Zn · kg^{-1} d.m.; g Cd, Pb, Zn · ha^{-1}) by organs of flax and linseed plants from sewage sludge-amended soil irrespective of tested cultivars and variant (data for 20 flax and linseed cvs. and 5 variant mixture sludge and soil). Analysis of variance; mature plants; field-simulated experiment 2005–2007

		Root	Stem	Capsule	Seed	Root	Stem	Capsule	Seed
		mg · kg^{-1}				g · ha^{-1}			
Flax	Cd	0.321^{a}	0.377^{a}	0.368^{a}	0.113^{a}	0.328^{a}	2.168^{a}	0.268^{a}	0.098^{a}
Linseed		0.318^{a}	0.474^{a}	0.420^{a}	0.153^{b}	0.280^{a}	2.220^{a}	0.447^{b}	0.199^{b}
Flax	Pb	1.141^{a}	0.867^{a}	1.918^{a}	0.542^{a}	1.099^{a}	4.405^{b}	1.467^{a}	0.542^{a}
Linseed		1.235^{a}	0.851^{a}	1.732^{a}	0.590^{a}	1.092^{a}	2.644^{a}	1.836^{b}	0.884^{b}
Flax	Zn	33.978^{a}	37.343^{a}	114.099^{a}	72.047^{b}	32.047^{b}	183.420^{b}	89.578^{a}	59.603^{a}
Linseed		32.997^{a}	37.928^{a}	118.679^{a}	67.695^{a}	27.018^{a}	118.162^{a}	115.072^{b}	81.381^{b}

of linseed Atalante in root (1.435 g Pb · ha^{-1}), variety of linseed Biltstar in capsules (2.414 g Pb · ha^{-1}) and variety of linseed Flanders in seed (1.028 g Pb · ha^{-1}) (Table 6). Linseed Flanders had higher accumulative potential Cd in seed (0.234 g · ha^{-1}). Stem and capsules absorbed more Cd by linseed Biltstar (3.986 g · ha^{-1}, 0.573 g · ha^{-1}) (Table 5). By monitoring of studied heavy metals during years there was found out various significant ($p \geq 0.05$) influence on their concentration an accumulation into parts of flax.

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WPŁYW OSADÓW ŚCIEKOWYCH W GLEBIE NA AKUMULACJĘ Cd, Pb ORAZ Zn W *Linum usitatissimum* L.

Abstrakt: Osad ściekowy jest produktem procesu oczyszczania ścieków. Osady ściekowe mogą być uznane za odpady niebezpieczne, wymagające kosztownych procedur usuwania, lub mogą być postrzegane jako źródło składników odżywczych do stosowania na gruntach rolnych. Badania przeprowadzono w symulowanych warunkach naturalnych – w doniczkach umieszczonych w ziemi na głębokości 50 cm, zawierających mieszaninę naturalnych osadów i gleb. Osady ściekowe dodano do odważonej ilości gleby w proporcjach: osady – gleba = 1:2 (var. K1), 1:3 (var. K2), 1:4 (var. K3), 1:5 (var. K4), 1:6 (var. K5). Wariant kontrolny (K0) bez obecności osadów ściekowych również obsiano wszystkimi odmianami. Badano odmiany lnu włóknistego i lnu oleistego. Odmiany lnu włóknistego i oleistego różnie kumulowały zwłaszcza metale; najwyższe stężenia zanotowano dla Zn, a następnie Pb i Cd. Najniższe stężenia Cd i Pb były analizowane w materiale siewnym (0,121 mg · kg^{-1}), a najwyższe stężenia Cd i Pb stwierdzono w łodydze (Cd = 0,396 mg · kg^{-1}) i kapsułkach nasiennych (Pb = 1,881 mg · kg^{-1}). Najwyższe stężenie Zn stwierdzono w kapsułkach nasiennych (115,015 mg · kg^{-1}), a najniższe w korzeniach (33,782 mg · kg^{-1}). Trend akumulacji Cd: łodyga > kapsułka nasienna > korzeń > nasiona, Pb: kapsułka nasienna > łodyga > korzeń > nasiona, Zn: kapsułka nasienna > nasiona > korzeń > łodyga. Wyniki badań i eksperymentów pokazują, że poszczególne odmiany lnu włóknistego i lnu oleistego wykazują zmienność umiejętności akumulacji metali ciężkich z gleby, a tym samym różne potencjały fitoremediacji.

Słowa kluczowe: *Linum usitatissimum* L., len włóknisty, len oleisty, kadm, ołów, cynk