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Bioaccumulation and Translocation of Heavy Metals in Plants Artichoke during Sewage Sediment in Podzols Soils

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ABSTRACT

Application of sewage sludge (SS) as a fertilizer contributes to the intensity of Zn, Ga, Y, Zr, Rh, Pb uptake by Jerusalem artichoke plants. Also, the translocation coefficients of Zn, Sr, Y, Rh, Pb vary in a wide range of values, depending on the level of use of SS. Jerusalem artichoke culture is characterized by a significant potential for biological absorption of Ni, Cu, Zn, Ga, Y, Nb and especially Rh, and the translocation coefficient of all studied heavy metals was >1. Jerusalem artichoke is characterized by certain features of intra-tissue pollution by heavy metals under the influence of SS application, which leads to an increase in this indicator compared to the application of mineral fertilizers in an equivalent dose of Zn, Y, Zr, as well as Ni, Cu, Ga, Sr, Nb, Pb in the highest doses (option 6). The use of SS composts with straw in the experiment leads to a significant decrease in intra-tissue pollution indicators compared to the application of fresh SS. Moreover, increasing the dose of compost from 20 t/ha to 30 t/ha contributes to the reduction of intra-tissue contamination of plants with Cu, Zn, Sr, Zr, Nb, Pb. The highest levels of the Integral indicator of vegetation cover pollution are determined by the application of fresh SS at the SS rate of 40 t/ha + $N_{10}P_{14}K_{58}$. Jerusalem artichoke culture, given its significant potential for translocation of heavy metals, can be successfully used for phytoremediation of technogenically polluted areas and grown with the introduction of SS as fertilizers.

Keywords: translocation, tissue pollution, integral indicator of plant pollution, biological absorption coefficient.

INTRODUCTION

Among the numerous strategies for the efficient utilization of sewage sludge (SS), applying it as a fertilizer to the soil is one of the most promising ways of using it for food, vegetable, and energy crops. The researchers note the significant impact of the use of SS on the change in the chemical composition of the soil, its agronomic and economic impact on the crops grown, the recycling of nutrients in agroecosystems (Eid E.M et al., 2020a; Eid E.M et al., 2020b; Lopushniak V. & Hrytsuliak H., 2021b; Skrylnyk Ye. et al, 2020). The use of SS leads not only to the improvement of the regime of mineral nutrition of plants, but also activates their assimilation of heavy metals (Naznin Nahar & Md. Shahadat Hossen, 2021). That is, the use of SS is associated with certain environmental risks, which relate to the possibility of the inclusion of heavy metals in trophic food chains (Alengebawy A et al, 2021; Alvarenga P., Farto M., Mourinha C. & Palma P., 2016; Elmi A., Al-Khaldy A., Al-Olayan M., 2020). Therefore, the risks and levels of heavy metal contamination of the soils on which SS are applied require constant monitoring and, if necessary, the implementation of bioremediation measures. For the bioremediation of soils contaminated with heavy metals, various strategies with varying degrees of effectiveness are being developed (Naeim A.H., Baharlouei J., Ataabadi M., 2021). As a key element of bioremediation, the cultivation of various types of wild and cultivated plants on such soils, which are characterized by a different degree of phytoaccumulation of heavy metals in different parts of the vegetative mass, is considered (Ebrahem M. Eid & Kamal H. Shaltout, 2016; Murtić S. et al, 2021).

Therefore, when growing different types of plants, it is important to evaluate their phytoaccumulative effect and the possibilities of their use for bioremediation of territories exposed to technogenic, agrochemical and other types of pollution (Lopushniak V. & Hrytsuliak H., 2021a), and also to establish the regularities of accumulation, i.e. biotranslocation of heavy metals in the soil-plant link, including for the introduction of SS into the soil.

The aim of the work is to evaluate the impact of the application of SS on the patterns of translocation of trace elements and HM in underground and above-ground parts of the vegetative mass of Jerusalem artichoke, as well as to establish the levels of plant contamination under the influence of increasing doses of fresh and composted SS.

MATERIAL AND METHODS

The research was conducted in the west of Ukraine in the Precarpathian region. The soil of the research area is podzolic. SS for research was taken from sludge maps of the Ivano-Frankivsk aeration station. The total area of the experimental site is 63.0 m^2, the accounting area is 35.0 m^2. The scheme of the experiment included: option 1 – control; option 2 – introduction of NPK at the rate of 60 kg/ha into the active substance; option 3 – introduction of NPK at the rate of 90 kg/ha in the active substance; the rest of the options (4–8) provided for the application of SS and composts based on it in different rates with a compensatory dose of mineral fertilizers at the rate of $N_{90}P_{90}K_{90}$, namely: option 4 – SS dose of 20 t/ha + $N_{50}P_{52}K_{74}$; option 5 – SS dose 30 t/ha + $N_{30}P_{33}K_{66}$; option 6 – SS dose 40 t/ha + $N_{10}P_{14}K_{58}$; option 7 – compost at a dose of 20 t/ha + $N_{50}P_{16}K_{67}$; option 8 – compost in a dose of SS 30 t/ha + $N_{30}K_{55}$. Composting (SS + straw in the ratio (3:1) was carried out for three months in the immediate vicinity of the experimental field.

Application of organic and mineral fertilizers - in the spring as the main fertilizer, immediately before planting. It is introduced into the soil with a disk harrow to a depth of 25–27 cm using mineral P and K before sowing crops and nitrogen N during early spring top dressing.

Soil samples were taken at a depth of 0–30 cm, and green mass and tubers were taken at the end of the growing season before harvesting, which in the experiment fell on the period of late September – early October, depending on weather conditions (the difference between the years of research did not exceed 7–9 days).

Physico-chemical analysis of soil and plant samples. The elemental composition of soil and plants was studied in one sample by X-ray fluorescence analysis on the EXPERT 3L analyzer. The volume of the studied sample is about 0.5 cm^3. The results of the study are presented in the order of placement of the elements of the periodic table to Fe. The absence of chemical elements in the list indicates insignificant and unreliable changes in indicators of their content according to all variants of the experiment.

In the samples, the coefficient of biological absorption (Cba) was calculated according to the formula:

$$Cba = Lx/Nx, \qquad (1)$$

where: Lx – is the content of the element in the plant, mg/kg; Nx – is the content of the element in the soil, mg/kg.

For the grouping of heavy metals in series according to the intensity of biological absorption, five gradations are used according to the methods (Samchuk, 2006, Miljutenko, 2014)

The index of intra-tissue pollution of plants was calculated according to the formula: (Gryshko, 2017)

$$I_{ITP} = \frac{Lx_i}{L_{control}} \qquad (2)$$

where: L_{X_i} – bridge element in the plant, mg/kg;
$L_{control}$ – element content in the plant (control), mg/kg.

Coefficients of translocation of heavy metals from the soil to the aerial and root parts of plants were calculated according to formula 3 (Kouchou, 2017, Miljutenko, 2014).

$$K_{THM} = \frac{c_{plant}}{c_{soil}} \quad (3)$$

where: c_{plant} – plant is the concentration of the element in the studied plant;
c_{soil} – the concentration of the element in the studied variant of the soil.

The studied elements do not represent the same level of danger for the biota. According to the classification of J. Wood (1972), according to their toxicity, they are divided into hazard classes, according to which the integral assessment of the contamination of the plant cover by heavy metals was determined based on the formula (Sobhanardakani and Ghoochian, 2016; Fatyeyev, 2003), with minor corrections proposed by us, the determination of the calculation of the integral indicator of vegetation cover pollution (4) will have the following form:

$$IS = 3\sum_{n=3}\frac{c_i^1}{c_{bi}} + 4\sum_{n=4}\frac{c_i^2}{c_{bi}} + 5\sum_{n=5}\frac{c_i^3}{c_{bi}} \quad (4)$$

where: IS – is an integral indicator of vegetation cover pollution;
c^1_i – the concentration of the ith pollutant in a plant of the 1st danger class, mg/kg;
c^1_{bi} – concentration of the ith pollutant in the plant of the 1st danger class of the control version of the research, mg/kg;
n_3 – the number of pollutants in a plant of the 1 hazard class;
c^2_i – the concentration of the ith pollutant in a plant of the 2 danger class, mg/kg;
c^2_{bi} – concentration of the ith pollutant in the plant of the 2 danger class of the control version of the research, mg/kg;
n_4 – the number of pollutants in a plant of the 2 danger class;
c^3_i – the concentration of the ith pollutant in a plant of the 3 danger class, mg/kg;
c^3_{bi} – background concentration of the *i*-th pollutant in a plant of the 3 danger class, mg/kg;
n_5 – the number of pollutants in a plant of the 3 danger class;
3, 4, 5 – coefficients that reflect the number of elements of the 1, 2 or 3 danger class.

All experimental measurements were performed in at least eight replicates, and results are presented as mean values based on correlation-regression analysis performed using STATISTICA 6.0.

RESULTS AND DISCUSSIONS

Studies have determined certain patterns of changes in the content of certain heavy metals in the soil, tubers and vegetative mass of Jerusalem artichoke under the influence of the use of SS and composts based on it and straw of grain crops (Table 1).

According to the data of experimental studies, the ambiguous influence of the use of SS in different forms on the patterns of accumulation of certain heavy metals in Jerusalem artichoke plants has been established. The use of increasing doses of SS compared to the introduction of its composts with straw led to a significant increase in the content of Cr, Ga, Sr, Y, Zr, Rb in the soil. However, the introduction of composts from the SS in a higher dose (option 8) ensured an increase in the content of Cu, Nb, Rh in the soil. For other elements (Ni, Zr, etc.), the dependence was not clearly expressed.

In the tubers and vegetative mass of Jerusalem artichoke, the introduction of increasing doses of SS led to an increase in the content of the vast majority of heavy metals determined in the experiment, except for Cu.

In general, the accumulation of heavy metals in plants was not directly proportional to the increase in their content in the soil under the influence of SS application.

A clear idea of the features of the accumulation of individual elements in plants is provided by the definition of the biological absorption coefficient (formula 1), which was calculated in the experiment as the ratio of the content of the element in the plant to its content in the soil (Table 2).

The coefficient of biological absorption of elements varied in a wide range of values, depending on the features of accumulation in tubers and above-ground (vegetative) mass of Jerusalem artichoke. The application of fresh SS contributed to the unconditional increase in biological absorption compared to the application of mineral fertilizers and SS composts with straw in an equivalent dose for Ga, Y, Zr, Rh. For certain elements, it was established that with smaller doses of fresh SS (20 t/ha) and a compensatory dose of mineral fertilizers, the biological absorption of Rb, Y, Nb, Rh significantly decreased compared to the introduction of an equivalent amount of mineral fertilizers, however, an increase in the dose to 40 t/ha caused certain increase of this

Table 1. The content of individual heavy metals in podzols soil at a depth of 0–30 cm (a), tubers (b) and vegetative mass (*c*) of Jerusalem artichoke after applying fertilizers based on SS and its composts with straw of grain crops, %*10^{-4} (average for 2018–2021)

Chemical element		Research option							
		1	2	3	4	5	6	7	8
Cr*	*a*	0.792±0.10	0.834±0.11	0.826±0.13	0.812±0.12	0.842±0.15	0.887±0.16	0.827±0.11	0.859±0.12
	b	0.591±0.10	0.711±0.10	0.741±0.11	0.631±0.09	0.792±0.09	0.844±0.08	0.691±0.10	0.684±0.10
	c	0.314±0.02	0.342±0.02	0.431±0.02	0.272±0.02	0.367±0.02	0.382±0.02	0.422±0.01	0.461±0.01
Ni*	*a*	0.192±0.03	0.226±0.03	0.227±0.03	0.259±0.03	0.245±0.03	0.246±0.03	0.262±0.02	0.232±0.02
	b	0.455±0.02	0.517±0.02	0.524±0.02	0.334±0.02	0.471±0.02	0.584±0.03	0.438±0.02	0.121±0.01
	c	0.215±0.01	0.112±0.01	0.122±0.01	0.105±0.01	0.133±0.02	0.164±0.02	0.127±0.02	0.143±0.02
Cu*	*a*	0.132±0.01	0.153±0.01	0.174±0.02	0.195±0.02	0.226±0.02	0.257±0.02	0.211±0.02	0.261±0.03
	b	0.345±0.02	0.414±0.02	0.453±0.02	0.496±0.03	0.381±0.02	0.236±0.01	0.294±0.01	0.238±0.02
	c	0.188±0.01	0.123±0.02	0.123±0.01	0.109±0.01	0.155±0.02	0.189±0.02	0.145±0.01	0.136±0.02
Zn*	*a*	0.126±0.02	0.115±0.02	0.164±0.02	0.155±0.02	0.193±0.02	0.143±0.01	0.125±0.01	0.147±0.01
	b	0.071±0.02	0.041±0.02	0.057±0.02	0.098±0.01	0.059±0.01	0.077±0.01	0.066±0.01	0.089±0.01
	c	0.161±0.02	0.224±0.02	0.224±0.02	0.266±0.02	0.274±0.02	0.331±0.02	0.277±0.02	0.255±0.02
Ga*	*a*	0.115±0.02	0.121±0.02	0.159±0.02	0.176±0.02	0.225±0.01	0.279±0.01	0.157±0.01	0.195±0.01
	b	0.176±0.02	0.125±0.02	0.153±0.02	0.146±0.02	0.293±0.02	0.318±0.01	0.136±0.01	0.197±0.01
	c	0.161±0.01	0.178±0.01	0.178±0.01	0.167±0.01	0.178±0.01	0.256±0.01	0.164±0.01	0.178±0.01
Rb*	*a*	0.683±0.04	0.715±0.04	0.752±0.05	0.723±0.04	0.721±0.04	0.779±0.03	0.753±0.02	0.771±0.04
	b	0.989±0.06	0.931±0.04	0.981±0.06	0.540±0.04	0.446±0.02	0.590±0.01	0.539±0.03	0.457±0.02
	c	0.647±0.01	0.963±0.01	0.961±0.01	0.154±0.01	0.219±0.01	0.276±0.01	0.128±0.01	0.166±0.01
Sr*	*a*	0.664±0.04	0.684±0.04	0.695±0.04	0.729±0.04	0.792±0.04	0.845±0.04	0.764±0.04	0.821±0.03
	b	0.791±0.03	0.873±0.03	0.835±0.03	0.764±0.02	0.564±0.02	0.921±0.04	0.985±0.03	0.815±0.03
	c	0.184±0.01	0.294±0.01	0.294±0.01	0.258±0.02	0.378±0.02	0.433±0.03	0.483±0.03	0.379±0.02
Y*	*a*	0.231±0.01	0.254±0.01	0.271±0.01	0.243±0.01	0.291±0.01	0.325±0.02	0.361±0.02	0.282±0.02
	b	0.152±0.01	0.186±0.01	0.170±0.01	0.193±0.01	0.217±0.01	0.264±0.01	0.249±0.01	0.213±0.01
	c	0.636±0.04	0.781±0.04	0.710±0.04	0.814±0.04	0.999±0.04	1.012±0.04	0.821±0.04	0.876±0.04
Zr*	*a*	0.325±0.01	0.331±0.01	0.364±0.01	0.376±0.01	0.434±0.02	0.394±0.01	0.421±0.01	0.432±0.02
	b	0.211±0.01	0.224±0.01	0.259±0.01	0.165±0.01	0.292±0.01	0.363±0.01	0.315±0.01	0.276±0.01
	c	0.213±0.01	0.215±0.01	0.285±0.01	0.322±0.01	0.344±0.01	0.375±0.04	0.389±0.04	0.361±0.01
Nb*	*a*	0.164±0.01	0.181±0.01	0.213±0.01	0.234±0.01	0.254±0.01	0.263±0.03	0.284±0.01	0.334±0.02
	b	0.171±0.01	0.121±0.01	0.125±0.01	0.141±0.01	0.185±0.01	0.198±0.01	0.168±0.01	0.159±0.01
	c	0.541±0.04	0.564±0.04	0.676±0.04	0.614±0.04	0.718±0.04	0.736±0.04	0.781±0.04	0.725±0.05
Rh*	*a*	0.002±1^{-1000}	0.001±1^{-1000}	0.002±1^{-1000}	0.001±1^{-1000}	0.001±1^{-1000}	0.002±1^{-1000}	0.011±1^{-1000}	0.011±1^{-1000}
	b	0.141±0.01	0.111±0.01	0.112±0.01	0.145±0.01	0.121±0.01	0.184±0.01	0.161±0.01	0.132±0.01
	c	0.645±0.04	0.756±0.04	0.786±0.04	0.814±0.04	0.718±0.04	0.837±0.04	0.711±0.04	0.730±0.04
Pb*	*a*	0.747±0.04	0.765±0.04	0.772±0.04	0.752±0.04	0.797±0.04	0.827±0.04	0.663±0.04	0.673±0.04
	b	0.355±0.02	0.321±0.04	0.311±0.04	0.392±0.04	0.412±0.04	0.457±0.02	0.632±0.04	0.461±0.02
	c	0.621±0.04	0.671±0.04	0.687±0.04	0.679±0.04	0.794±0.04	0.938±0.04	0.964±0.04	0.851±0.06

Table 2. Change in the coefficients of biological absorption of heavy metals for the introduction of SS under Jerusalem artichoke, average for 2018–2021

Chemical element	Research option							
	1	2	3	4	5	6	7	8
Cr*	0.39	0.41	0.52	0.33	0.43	0.43	0.51	0.53
Ni*	1.11	0.49	0.53	0.40	0.54	0.66	0.48	0.61
Cu*	1.42	0.80	0.70	0.55	0.68	0.73	0.68	0.52
Zn	1.27	1.94	1.36	1.71	1.41	2.31	2.21	1.73
Ga*	1.41	1.47	1.11	1.79	1.99	2.34	1.06	1.53
Rb*	0.94	1.34	1.27	0.21	0.30	0.35	0.16	0.21
Sr*	0.27	0.42	0.42	0.35	0.47	0.51	0.63	0.46
Y*	2.75	3.07	2.61	3.34	3.43	3.62	2.27	3.10
Zr*	0.65	0.64	0.78	0.85	0.79	0.95	0.92	0.83
Nb*	3.29	3.11	3.17	2.62	2.82	2.79	2.75	2.17
Rh*	322	756	393	814	718	418	155	161
Pb*	0.83	0.87	0.88	0.90	1.00	1.13	1.45	1.26

indicator. The biological absorption of Cr, Rb, Nb by the Jerusalem artichoke culture under the influence of the application of SS significantly decreased compared to the option where only mineral fertilizers were applied, while Zn, Ga, Y, Rh, Pb increased significantly.

The increase in the Kbp for certain elements in the options with the introduction of SS led to an increase in the index of intra-tissue pollution (IITP) (formula 2) by heavy metals in comparison with the option where only mineral fertilizers were applied in an equivalent dose (option 3), except for Cr, Rb (Table 3).

The application of SS results in a significant increase in the index of intra-tissue pollution compared to the application of mineral fertilizers in an equivalent dose of Zn, Y, Zr, as well as Ni, Cu, Ga, Sr, Nb, Pb in the highest doses (option 6). The use of SS composts with straw in the experiment based on the calculation of $N_{90}P_{90}K_{90}$ leads to a significant decrease in the indicators of intra-tissue contamination compared to the application of fresh SS. Moreover, increasing the dose of compost from 20 t/ha to 30 t/ha contributes to the reduction of intra-tissue contamination of Cu, Zn, Sr, Zr, Nb, Pb.

In addition to the Index of intra-tissue pollution, the coefficients of translocation of heavy metals were determined in the studies (Table 4), reflecting the ratio of their content in the plant part to the mobile form in the soil (formula 3).

Table 3. The impact of the use of SS on the change in the value of the index of intra-tissue contamination of Jerusalem artichoke plants with heavy metals, average for 2018–2021

Chemical element	Research option						
	2	3	4	5	6	7	8
Cr*	1.08	1.37	0.86	1.16	1.21	1.34	1.46
Ni*	0.52	0.56	0.48	0.61	0.76	0.59	0.66
Cu*	0.65	0.65	0.57	0.82	1.01	0.77	0.72
Zn	1.39	1.39	1.65	1.70	2.05	1.72	1.58
Ga*	1.10	1.10	0.97	1.10	1.93	0.94	1.05
Rb*	1.48	1.48	0.23	0.33	0.42	0.19	0.25
Sr*	1.59	1.59	1.40	2.05	2.35	2.62	2.05
Y*	1.22	1.11	1.23	1.57	1.58	1.29	1.37
Zr*	1.00	1.33	1.51	1.61	1.76	1.82	1.69
Nb*	1.04	1.24	1.13	1.32	1.36	1.44	1.34
Rh*	1.17	1.21	1.26	1.11	1.29	1.10	1.12
Pb*	1.08	1.10	1.09	1.27	1.51	1.55	1.37

Table 4. The change in the translocation coefficient of heavy metals in Jerusalem artichoke plants depending on the application of SS, the average for 2018–2021

Chemical element	Research option							
	1	2	3	4	5	6	7	8
Cr*	1.14	1.26	1.41	1.11	1.37	1.38	1.34	1.33
Ni*	3.48	2.78	2.84	1.69	2.46	3.04	2.15	1.13
Cu*	4.04	3.5	3.31	3.10	2.30	2.39	2.08	1.43
Zn	1.84	2.30	1.71	2.34	2.52	2.85	2.14	2.34
Ga*	2.91	2.50	2.08	2.85	2.98	3.85	2.85	2.91
Rb*	2.39	2.64	2.58	0.95	0.92	1.12	0.88	0.80
Sr*	1.46	1.70	1.62	1.50	1.68	1.84	1.52	1.65
Y*	3.41	3.80	3.24	4.14	4.17	3.34	2.96	3.86
Zr*	1.30	1.32	1.49	1.29	1.46	1.87	1.67	1.47
Nb*	4.34	3.78	3.76	3.22	3.55	3.55	3.34	2.64
Rh*	393	867	449	959	839	510	182	189
Pb*	1.30	1.29	1.29	1.42	1.52	1.68	1.40	1.52

In the options where SS was introduced, these indicators of Zn, Ga, Y, Rh translocation were the highest in the experiment, compared to other options of the experiment. However, the translocation coefficient of Ni, Cu, Rb, Nb was lower compared to the similar indicator on the control variant and variants where only mineral fertilizers were applied. The coefficient of translocation of two elements, Cu and Rh, decreased as the SS dose increased. In the variants with the use of composts with SS and straw, the translocation coefficients decreased compared to the variants of applying fresh SS. An increase in the dose of compost application contributed to a significant decrease in the coefficient of translocation for Ni, Cu, Zr, Nb, Pb, and the coefficient of translocation Y increased significantly by 1.3–2.5 times compared to the control variant. It should be emphasized that Jerusalem artichoke under the conditions of the experiment was characterized by a radical increase in the Rh translocation coefficient, which ranged from 180 in the variants with the application of composts of SS with straw to 960 in the variants where fresh SS was applied.

The analysis of the translocation indicators of individual elements in Jerusalem artichoke plants does not provide a complete description of the degree of contamination of the plant cover. For a generalized assessment of the level of contamination of Jerusalem artichoke plants with heavy metals, the Integral index of contamination was calculated according to the proposed formula 4 (Fig. 1).

The integrated indicator of Jerusalem artichoke plant pollution was the lowest (52) in the variant where the lowest dose of SS was applied (option 4) with the corresponding amount of mineral fertilizers, and the highest (70) in the variant where the highest rate of SS was applied

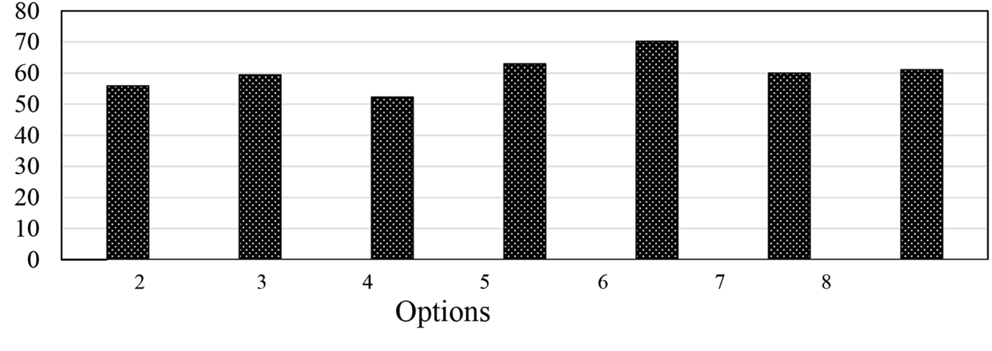

Figure 1. Integral indicator of vegetation cover pollution due to the introduction of sewage sludge under Jerusalem artichoke

(option 6). In the options where mineral fertilizers and composts based on SS and straw with a compensatory dose of mineral fertilizers were applied (options 2, 3 and 7, 8), the value of this indicator was at the level of 55–60.

For options where mineral fertilizers were applied at the rate of $N_{90}P_{90}K_{90}$ and fresh SS with an appropriate dose of mineral fertilizers (options 3, 4, 5 and 6), the multiple regression equation of the dependence of the integral indicator of vegetation cover pollution on increasing doses of SS was calculated, which can have the following form:

$$y = 13.029x - 0.5664 \qquad (5)$$

where: x – is the rate of application of SS, t/ha;
y – Integral indicator of vegetation cover pollution.

The high closeness of the relationship between plant pollution and the rate of application of SS is reflected by the coefficient of determination, which is $R^2 = 0.79$.

The calculated statistical model of the dependence of the Integral pollution of the plant cover on the coefficients of biological absorption and translocation for elements of the 1st danger class (Fig. 2) also reflects the high closeness of the connection between these indicators. For Lead, the regression equation can look like this:

$$z = 18.9837 - 34.5775x + 109.3581y \qquad (6)$$

where: z – is the integral indicator of vegetation cover contamination; x – coefficient of Lead translocation; y – is the coefficient of biological absorption of lead.

For this dependence, the multiple coefficients of determination is ($R^2 = 0.72$), the correlation coefficient $r = 0.68$. For Rhodium, the equation will look like this:

$$z = 51.2314 - 0.0476x + 0.061y \qquad (7)$$

where: z – is an integral indicator of pollution;
x – Rhodium translocation coefficient;
y – is the coefficient of biological absorption of rhodium.

The value of the multiple coefficients of determination ($R^2 = 0.76$) and the correlation coefficient ($r = 0.69$) also indicate a high closeness of the relationship. Calculated models of the dependence of the Integral indicator of vegetation cover pollution on the Biological Absorption Coefficient and the Translocation Coefficient for some elements of the 2nd class of danger (Fig. 3). For copper, the regression equation can look like this:

$$z = 12.4103 - 12.8464x + 121.1375y \qquad (8)$$

where: z – is an integral indicator of pollution;
x – copper translocation coefficient;
y – coefficient of biological absorption of copper.

Multiple coefficients of determination ($R^2 = 0.73$) and correlation coefficient ($r = 0.66$) indicate a close correlation between these indicators. For Nickel, the regression equation can look like this:

$$z = -45.3656 + 15.1684x + 129.0606y \qquad (9)$$

where: z – is an integral indicator of pollution;
x – is the nickel translocation coefficient;
y – is the coefficient of biological absorption of nickel.

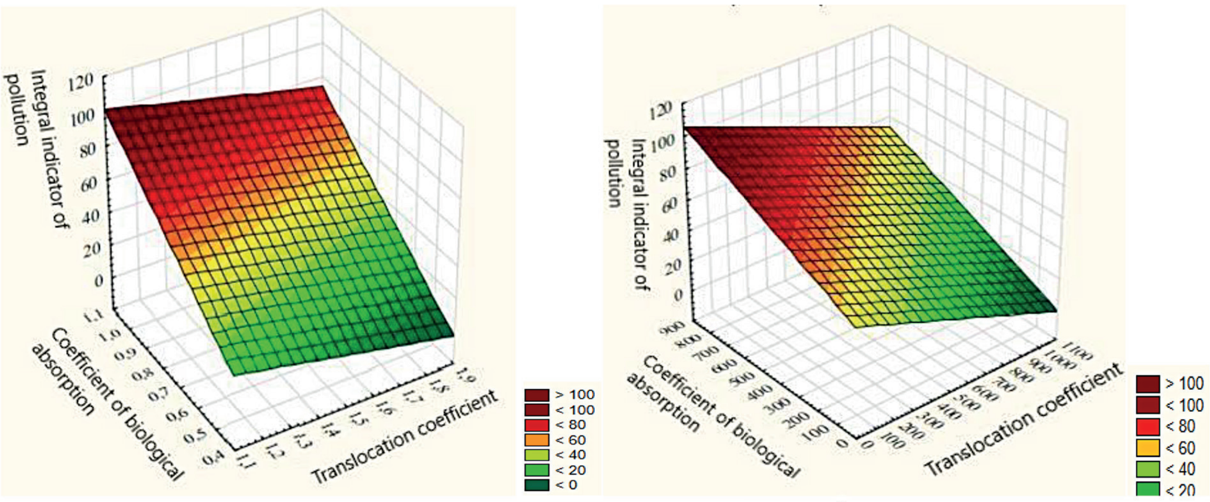

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Figure 2. Model of the dependence of the indicator of the Integral assessment of vegetation cover pollution on the coefficient of biological absorption and the coefficient of translocation for (a) Lead and (b) Rhodium.

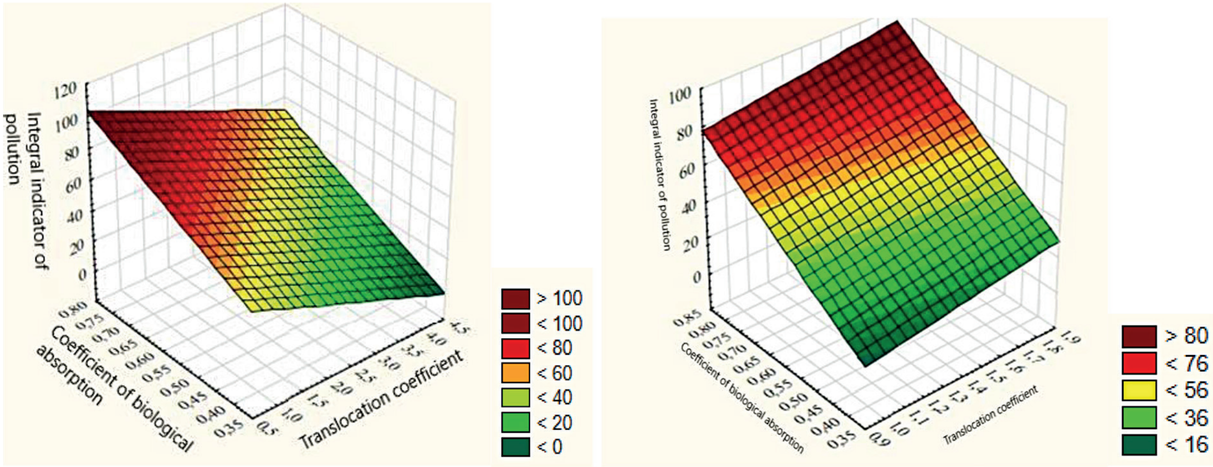

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Figure 3. Model of the integral indicator of vegetation cover pollution from the biological absorption coefficient and the translocation coefficient for Copper (a) and Nickel (b)

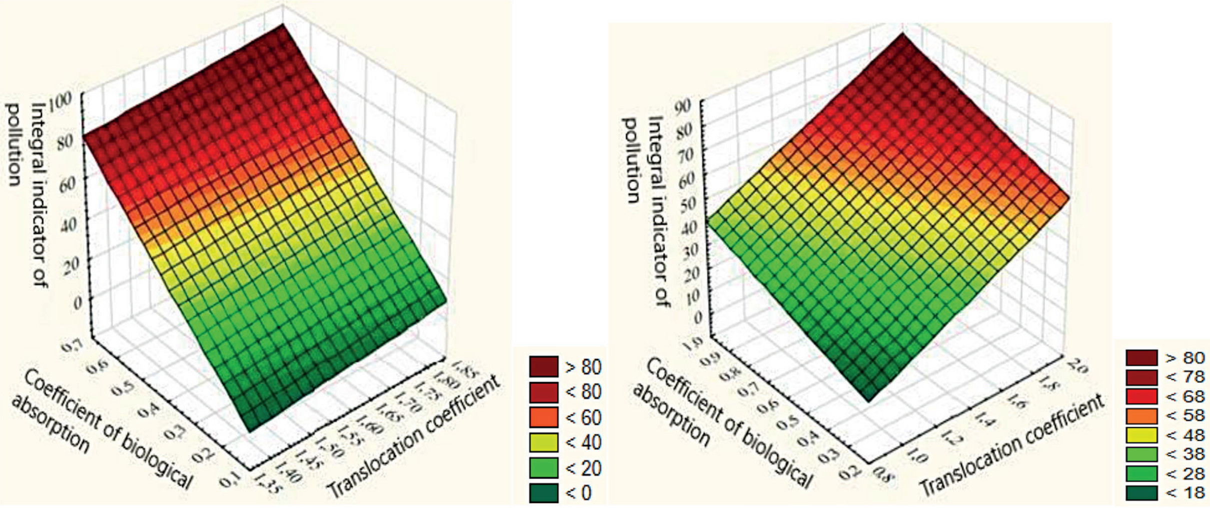

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Figure 4. Model of the dependence of the integral indicator of vegetation cover pollution on the biological absorption coefficient and the translocation coefficient for Strontium (a) and Zirconium (b)

The coefficients of dependence are, respectively: multiple coefficient of determination – ($R^2 = 0.71$), correlation coefficient – ($r = 0.65$).

The model of the integral indicator of vegetation pollution from the biological absorption coefficient and the translocation coefficient for some elements of the 3rd hazard class is noted (Fig. 4). For Strontium, the regression equation can look like this:

$$z = -44.2514 + 21.7011x + 135.5182y \quad (10)$$

where: z – is an integral indicator of pollution;
x – strontium translocation coefficient;
y – is the coefficient of biological absorption of strontium.

The coefficients of dependence are, respectively: multiple coefficient of determination – ($R^2 = 0.69$), correlation coefficient – ($r = 0.62$).

For Zirconium, the regression equation can look like this:

$$z = -17.9803 + 35.0043x + 30.3379y \quad (11)$$

where: z – is an integral indicator of pollution;
x – zirconium translocation coefficient;
y – is the coefficient of biological absorption of zirconium.

The coefficients of dependence are, respectively: multiple coefficient of determination – ($R^2 = 0.74$), correlation coefficient – ($r = 0.66$).

CONCLUSIONS

Jerusalem artichoke culture is characterized by a significant potential for biological absorption of heavy metals, namely Ni, Cu, Zn, Ga, Y, Nb and especially Rh (Kbp > 1). The introduction of SS as a fertilizer causes significant changes in the biological absorption of heavy metals, namely, it contributes to a significant increase in the absorption of Zn, Ga, Y, Zr, Rh, Pb compared to the control option, where no fertilizers were applied.

The coefficients of heavy metal translocation in Jerusalem artichoke plants varied in a wide range of values depending on the application of SS, in particular, a significant increase in the translocation of Zn, Sr, Y, Rh, Pb was noted. Jerusalem artichoke culture is characterized by a significant potential for translocation of heavy metals, since the translocation coefficient in all variants of the experiment is greater than 1.

Depending on which heavy metals the ground cover is contaminated with, it is possible to choose different strategies for the phytoaccumulation of polluting elements, since under the influence of changes in the mineral regime of culture nutrition, the features of translocation of heavy metals also change.

Jerusalem artichoke is marked by certain features of intra-tissue contamination with heavy metals under the influence of the application of SS, which leads to an increase in this indicator compared to the application of mineral fertilizers in an equivalent dose of Zn, Y, Zr, as well as Ni, Cu, Ga, Sr, Nb, Pb in the highest doses (option 6). The use of SS composts with straw in the experiment leads to a significant decrease in intra-tissue pollution indicators compared to the application of fresh SS. Moreover, increasing the dose of compost from 20 t/ha to 30 t/ha contributes to the reduction of intra-tissue contamination of Cu, Zn, Sr, Zr, Nb, Pb.

The calculated levels of the Integral indicator of vegetation cover pollution reflect its dependence on increasing doses of SS (multiple coefficient of determination is $R^2 = 0.79$). The use of SS determines the value of this indicator at the level of 52–70, and mineral fertilizers and composts based on SS and straw of grain crops – 55–60.

Thus, Jerusalem artichoke culture, given its significant potential for translocation of heavy metals, can be successfully used for phytoremediation of technogenically polluted areas and grown with the introduction of SS as fertilizers.

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