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Accumulation of Heavy Metals in *Silphium Perfoliatum* L. for the Cultivation of Oil-Contaminated Soils

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ABSTRACT

The article presents the results of research on the effectiveness of the use of crops of *Silphium Perfoliatum* L. for phytoremediation of soils in oil-contaminated areas. *Silphium Perfoliatum* L. is characterized by unique opportunities for productivity and longevity, can be cultivated in one place for many years. The aim of our work was investigating the rate of accumulation of heavy metals in the aboveground and root mass of *Silphium Perfoliatum* L. during the introduction of sewage sludge in oil-contaminated areas. The research was conducted in the Precarpathians of Ukraine in Ivano-Frankivsk region. The experimental field is slightly sod-podzolic sandy, there are several remnants of oil spills, the so-called oil slicks. The experiment included 8 options of fertilizing *Silphium Perfoliatum* L. In soils of contaminated areas determined content of total and mobile forms of metals and their content in the green mass and plant roots by methods according to ISO 4770.3 – GOST 4770.9, atomic adsorption methods in the lab of Ivano-Frankivsk State Institution branch "Soil Protection". The metal translocation coefficient in the system «soil-vegetative mass» and in the system «soil-root» increases in a number: Cd → Ni→ Cot → Pb. That is, the lowest translocation coefficient is in the lead. However, the difference is that in the system «soil-root» the coefficient of translocation is higher by 2–3%, from the translocation of metals in the system «soil – vegetative mass». The coefficient of biological accumulation of heavy metals by perforated sylph increase in a number of elements: Pb → Co → Ni → Cd.

Keywords: metals, *Silphium Perfoliatum* L., oil-contaminated territory, accumulative capacity, contaminated area, studied soil.

INTRODUCTION

Oil pollution is a serious threat for soil and plants (Ilyas et al., 2021). Contamination of soils with oil and products of its processing causes significant processes of ecosystem degradation (Ait Elallem, et al. 2021; Ghori, 2019, Radu Sumalan, 2020). Due to its adsorbing properties, petroleum products are stored in the soil for a long time, thus changing its physicochemical and biological properties. Petrochemical pollution with a high content of heavy fractions of hydrocarbons forms a dense, viscous bituminous crust on the soil surface, which hinders gas exchange between air and soil environment (Yakovleva, 2021; Cho-Ruk et al., 2006; Gamayunova et al., 2021). In addition, almost all soils that were exposed to man-made impact due to the construction or operation of oil pipelines (product pipelines) were man-made, contaminated with heavy metals, pollutants, etc. Heavy metals are especially dangerous due to their ability to bioaccumulate (Bekuzarova, 2021; Ilyas, 2021; Cui X., 2021; Faruqui, 2004; Mazurenko et al., 2020).

Natural restoration of soil ecosystems contaminated with petroleum products is a long and complex process. It causes an urgent need to find effective and environmentally friendly methods of cleaning the environment from oil pollution, as well as to restore the state of the soil environment (Gaur, 2004; Rakhshaee et al., 2009; Gamayunova et al., 2021).

Elimination and elimination of negative consequences of oil contamination of the soil cover is carried out by various methods (combustion, steam extraction, washing of oil-contaminated soil, sorption, restoration of territories with initiated humic sorbent, use of activated peat, cleaning of hard surfaces with hydrophobic oil, etc.) (Sarapulova, 2021; Ghazala, 2016). Analysis of the literature gives grounds to claim that the known mechanical, chemical and physical methods are long-lasting, costly and do not provide complete purification of the environment (Taketani, 2021; Ait Elallem et al., 2021; Sivkov, 2021).

An alternative and relatively energy-saving method is the phytoremediation of oil-contaminated areas, which is based on the cultivation of cultivated plants, including energy (candlegrass, energy willow, miscanthus, Jerusalem artichoke, etc.), which intensively accumulate vegetative mass during many cycles. its subsequent alienation from the field. One of such phytoremediator plants may be *Silphium perfoliatum* L. (Saet Yu, 1989; Eissa, 2014).

Silphium Perfoliatum L. is characterized by unique opportunities for productivity and longevity, can be cultivated in one place for over 60 years (Gaur and Adholeya, 2004; Faruqui et al., 2004). According to literature sources (Montalbán et al., 2016; Ghazala and Setsuko, 2017; Ghori at al., 2019; Yakovleva, 2021) from each hectare of sowing *Silphium Perfoliatum* L. for 20–25 years provides an average of 70–100 tons or more of green mass. The vegetative mass of *Silphium Perfoliatum* L. begins to collect from the second year of the growing season. It can be used for fodder purposes, well ensiled alone or in a mixture with other plants, because in the flowering phase contains many sugars (Shtangeeva et al., 2004; Cho-Ruk et al., 2006). The plant is cold-resistant, withstands frosts in winter to minus 30–35°C (Gaur and Adholeya, 2004; Rakhshaee, Giahi, and Pourahmad, 2009; Hinchman, et al., 1995). *Silphium Perfoliatum* L. is unpretentious to soils, well withstands short droughts. The vegetative mass of this plant can be successfully grown for energy purposes (Burt, 2004; Rovira, 2021).

An important biological feature of *Silphium Perfoliatum* L. is its ability to absorb pollutants and heavy metals from the soil (Burt et al., 2004; Eissa et al., 2004; Vysotskaya, 2021.) The danger of accumulation of the studied elements in the soil environment is a negative effect on environmental, physicochemical, biological functions, complex degradation of soil (Cho-Ruk et al., 2006; Lasat, 2000; Faruqui et al., 2004). Restoration of contaminated and chemically degraded soils is one of the most urgent problems today. During the development of phyto-treatment of soils, including man-made contaminated with petroleum products, a special role is played by determining the forms and degree of mobility of HM in the soil-soil solution-plant ecosystem, including the cultivation of sylphia perforated (Eissa et al., 2004; Eissa, 2016; European Commission, 2002).

Silphium Perfoliatum L. forms a significant amount of vegetative mass over many years of vegetation, so there is a problem of studying the effectiveness of various types of long-acting fertilizers, including SS, which, with scientifically sound application, promotes microbiological processes in the soil (Lopushnyak & Hrytsulyak, 2021) causes improving the physico-chemical and agrochemical parameters of the soil (Lopushnyak et al, 2022; Lopushnyak et al, 2021), helps to increase the productivity of perennial energy crops, (Faruqui et al., 2004; Lopushnyak & Hrytsulyak, 2021; Lopushnyak et al., 2022). The value of sludge as a fertilizer provides the presence in its composition of macro-and micronutrients, primarily nitrogen, phosphorus, potassium (Taketani, 2021). These fertilizers are not inferior in efficiency to traditional organic fertilizers. On the other hand, the introduction of SS due to the possible content of a certain amount of heavy metals, can have a negative impact on soil systems and the ecological state of agroecosystems. Our previous studies (Lopushnyak & Hrytsulyak, 2021) showed high efficiency of SS application and a positive effect on the productivity and yield of *Silphium Perfoliatum* L. (Lopushnyak et al., 2022; Ghazala, 2016). The Use of various additives reduces soil toxicity (Sivkov & Nikiforov, 2021).

Therefore, there is a need to study the features of accumulation of the studied metals in the the root of the plant and its aboveground mass of *Silphium Perfoliatum* L. with the addition of sediment, especially in growing conditions in contaminated areas.

MATERIALS AND METHODS

The research was conducted in the Precarpathians of Ukraine on the site of the South – Hvizdetsky field of Nadvirna oil and gas district in the village. Bytkiv, Ivano-Frankivsk region. Production activity has not been carried out for 25 years. The width of the experimental plot is 5.0 m; length 7.0 m; registration area – 35 m^2. *Silphium Perfoliatum* L. was sown according to the scheme of 0.50×0.70 m. The uncontaminated area of the experimental field was selected as a control area.

The experimental field is slightly sod-podzolic sandy, there are several remnats of oil, the so-called oil slicks. The experiment included the following options for fertilizing sylphia perforated: 1 –8 options (Lopushnyak & Hrytsulyak, 2021; Lopushnyak & Hrytsulyak, 2020).

In soils of contaminated areas determined content of total and mobile forms of HM and HM in the vegetative mass and plant roots by methods according to ISO 4770.3 – GOST 4770.9, atomic adsorption methods (Tonkha at al., 2021; DSTU 4770.3: 2007; DSTU 4770.5: 2007; DSTU 4770.7: 2007; DSTU 4770.9: 2007) in the laboratory of Ivano-Frankivsk branch State Institution "Soils Protection Institute of Ukraine". The CBA was determined according to the methods according to the ratio of the content of the element in the ash of plants to its gross content in the soil (Korsun et al., 2019; Saet et al., 1989). The coefficient of absorption of the element was calculated by the formula Avessalomova (Avessalomova, 1987; Tonfha et al., 2018). The coefficients of transition of HM from the root system of sylphia perforated to the aboveground part of the plant were calculated by the ratio of the element content in the aboveground part of the plant to its content in the roots of *Silphium Perfoliatum* L. (FAO, 1985; Ghosh et al., 2012; Eissa, 2014).

RESULTS AND DISCUSSION

The increase in the content of mobile forms of nickel in the soil during the cultivation of *Silphium Perfoliatum* L. causes a maximum increase in the accumulation of cobalt by the vegetative mass of sylphia perforated (correlation coefficient 0.98). The highest correlations were found between the content of cobalt in the studied soil and the content of lead and cobalt in the vegetative mass of *Silphium Perfoliatum* L. Cadmium and lead show a mutual synergistic effect when moving from the soil to the aboveground mass of *Silphium Perfoliatum* L. The mobile form of nickel in the studied soil during the cultivation this crop has the maximum synergistic effect on the absorption of cadmium, nickel and cobalt by the roots of the plant (Table 1).

Mobile forms of cadmium in the studied soil have a weak negative effect on the absorption of nickel, lead, and cobalt by the root system of *Silphium Perfoliatum* L. The coefficient of transition of HM from the root system to the aboveground part of the *Silphium Perfoliatum* L are shown in Figure 1.

The conversion rate of cadmium in the options for the introduction of sewage sludge (SS) at a rate of 20 – is equal to 1.10–1.22, for the introduction of composts at a rate of 20 – (variants 7 and 8) is equal to 1.23–1.30. The conversion factor of nickel in the options for the introduction of SS at a rate of 20 – (variants 4–6) is 1.04–1.12, for the addition of compost at a rate of 20 – (variants 7 and 8) is equal to 1, 10–1.14, which is 0.25–0.29 higher than the control (Lopushnyak & Hrytsulyak, 2021; Lopushnyak et al. 2021).

The coefficient of transition of lead in the options for the introduction of SS at the rate of 20 – (variants 4 – 6) is equal to 1.23–1.41, which is 0.19–0.37 higher than the control. However, for the introduction of compost at the rate of 20 – (options 7 and 8) is equal to 1.20–1.31, which is 0.03–0.10 less than the options where fresh

Table 1. The correlation coefficients between the mobile forms content of metals in the studied soil, boveground and root mass of *Silphium Perfoliatum* L., average for 2016–2020 (Lopushnyak & Hrytsulyak, 2021)

Content in the soil	Aboveground part of the plant				Roots			
	Cd	Ni	Pb	Co	Cd	Ni	Pb	Co
Pb	0.82	0.72	0.75	0.64	0.65	0.71	0.72	0.68
Cd	0.80	0.83	0.89	0.86	0.83	0.85	0.43	0.77
Ni	0.87	0.94	0.97	0.98	0.96	0.93	0.89	0.90
Co	0.75	0.86	0.92	0.92	0.90	0.89	0.79	0.82

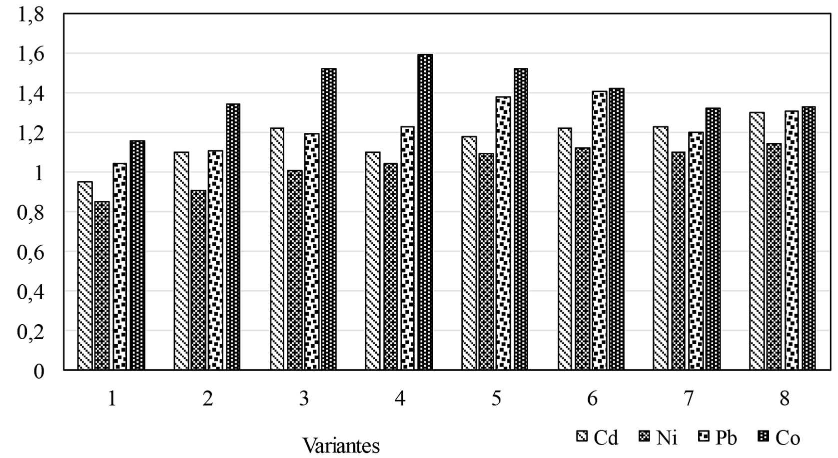

Figure 1. The transition coefficient of the heavy metals in the system "root-green mass" of *Silphium Perfoliatum* L. with the application of fertilizers based on sewage sludge, the average for 2016–2020

SS were applied. The coefficient of Co- element transition from the root system to the aboveground part of the *Silphium Perfoliatum* L. in the variants where SS was applied at the rate of 20 – are equal to 1.59–1.42. An increase in the transition of heavy metals from the root system to the aboveground mass was revealed for *Silphium Perfoliatum* L. in the series: Ni → Cd → Pb → Co (Lopushnyak & Hrytsulyak, 2021).

The highest translocation coefficient of cadmium in the system «soil-vegetative mass» of *Silphium Perfoliatum* L was recorded for the introduction (variant 4) is 4.12, Ni – for the addition of compost (variant 8) and is 0.97, Co and Pb – for the introduction of Ss in the studied soil (variant 6) are 0.38 and 0.21, respectively (Table 2) (Lopushnyak & Hrytsulyak, 2021).

The highest coefficient of translocation of Cd, Ni in the system «soil-root» of *Silphium Perfoliatum* L. are noted in the control version and are 5.48 and 0.87, respectively, Pb and Co – for compost at a rate of and $N_{30}K_{55}$ and is 0.22 and 0.27, respectively. Also, the highest transition rates of lead are observed for the addition of compost at the rate of and $N_{50}P_{16}K_{67}$ (option 7), Co – for the addition of SS at the rate of and $N_{10}P_{14}K_{58}$ (variant 8) (see Table 2) (Lopushnyak & Hrytsulyak, 2021; Lopushnyak et al., 2022).

The relation between the lead content in the vegetative mass and the metal content in the *Silphium Perfoliatum* L root in the studied soil by applying the fertilizer on the SS, ie the more test metal is in the green mass, respectively, it is contained in the root and soil (Fig. 2) (Lopushnyak & Hrytsulyak, 2021).

With the introduction the SS at a rate of 20– (variants 4–6) the lead content in the vegetative mass reached 0.74–0.97 mg/kg of plant, the content and 0.74–0.97 mg/kg of plant in the root system it was respectively and in the studied soil – 4.0–4.54 mg/kg of the soil with the compost introduction at a rate of 20 – (variants 7–8) the lead

Table 2. Translocation coefficient of metals for the cultivation *Silphium Perfoliatum* L, the average for 2016–2020 (Lopushnyak & Hrytsulyak, 2021)

Variant	Pb	Cd	Ni	Co	Pb	Cd	Ni	Co
	"Soil - vegetative mass"				«Soil-Root»			
Without fertilizer (control)	0.13	5.19	0.74	0.21	0.15	5.48	0.87	0.18
$N_{60}P_{60}K_{60}$	0.15	5.00	0.76	0.26	0.17	4.54	0.84	0.19
$N_{90}P_{90}K_{90}$	0.15	3.79	0.81	0.31	0.17	3.10	0.81	0.20
SS – 20 т/га + $N_{50}P_{52}K_{74}$	0.19	3.89	0.84	0.35	0.21	3.74	0.81	0.22
SS – 30 т/га + $N_{30}P_{33}K_{66}$	0.21	3.97	0.89	0.37	0.21	2.93	0.81	0.25
Sewage sludge B – 40 т/га + $N_{10}P_{14}K_{58}$	0.21	4.12	0.94	0.38	0.24	2.49	0.84	0.27
Compost ((Ss) + straw in the ratio 3: 1) 20 t / ha + $N_{50}P_{16}K_{67}$	0.19	5.52	0.95	0.35	0.22	4.48	0.86	0.26
Compost ((Ss) + straw in the ratio 3: 1) 30 t / ha + $N_{30}K_{55}$	0.21	3.98	0.97	0.36	0.22	3.07	0.85	0.27

content in the root of the system of S*ilphium Perfoliatum* L, respectively, was 0.66– 0.70 mg/kg of plant, and in the studied soil – 4.15–4.48 mg/kg of soil (Lopushnyak et al., 2021).

$$z = –0.8332 + 0.2073 \cdot x – 1.1459 \cdot y$$

where: z – is the lead content in the green mass, y – the lead content in the root system.

The multiple coefficients of determination (R^2 = 0.72) indicate a close correlation between these indicators. The relationship between the Cd content in the vegetative mass and the metal content in the root system of *Silphium Perfoliatum* L. and in the studied soil (Fig. 3).

With the introduction of the SS at a rate of 20– (variants 4–6) the Cd content in the vegetative mass reached 1.40–1.67 mg/kg of plant, the Cd content in the root system was 1.26–1,37 mg/kg of plant, and in the studied soil – 0.34–0.55 mg/kg of soil. With the compost application at a rate of 20– (variants 7–8) the Cd content in the vegetative mass reached 1.6–1.71 mg/kg, the cadmium content in the root system of *Silphium Perfoliatum* L., respectively, was 1.30–1.32 mg/kg of plant, and in the studied soil – 0.29–0.43 mg/kg of soil (Lopushnyak et al. 2021, 2022).

$$z = 0.968 + 7.7705 \cdot x – 2.8448 \cdot y + 0,5301 \cdot x^2 – 5.9219 \cdot xy + 2.4464 \cdot y^2$$

z – is the Cd content in the vegetative mass,
x – Cd content in the studied soil,
y – Cd content in the root system.

The multiple determination coefficient (R^2 = 0.80) indicates a high correlation between these indicators. The relationship between the nickel content in the vegetative mass and the content of this metal in the root system of *Silphium Perfoliatum* L. and in the studied soil (Fig. 4).

With the introduction of SS at a rate of 20– (variants 4–6), high correlation between these indicators. The relationship between the nickel content in the vegetative mass and the metal content in the vegetative mass and this metal content in the root system, respectively, was 1.14–1.29 mg/kg of plant, and in the studied soil – 0.65–0.82 mg/kg of soil. With the addition of composts at the rate

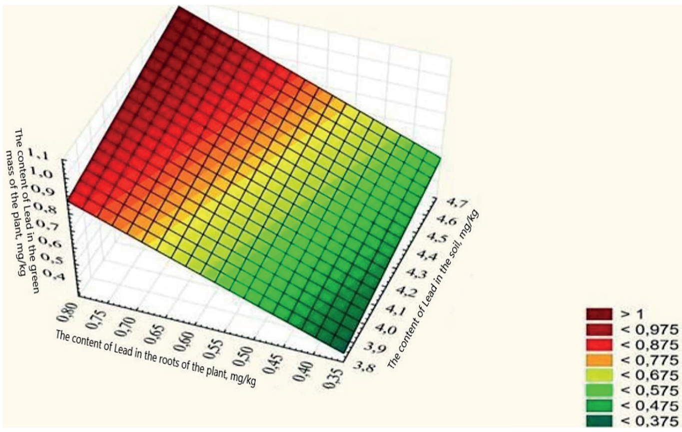

Figure 2. The dependence of the Lead content in the vegetative mass on the metal content in the *Silphium Perfoliatum* L. roots and in the soil, the average for 2016–2020

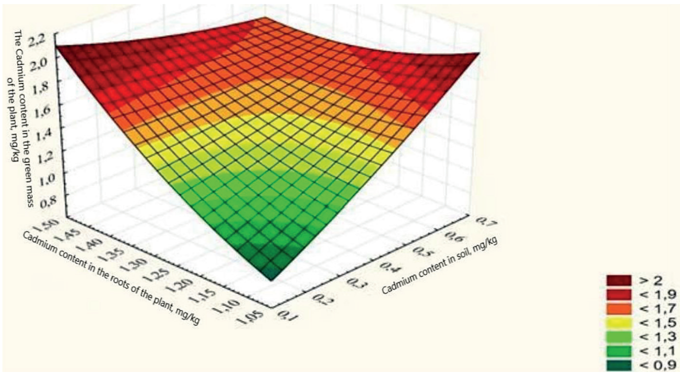

Figure 3. The cadmium content dependence in the vegetative mass on the metal content in the roots of *Silphium Perfoliatum* L. and in the studied soil, the average for 2016–2020

of 20 – (variants 7–8), the nickel content in the vegetative massreached 1.3–1.4 mg/kg of plants, in the root system of *Silphium Perfoliatum* L., respectively, was 1.18–1.24 mg/kg of plants, and in the studied soil – 1.37–1.46 mg/kg of soil (Lopushnyak et al. 2021, 2022).

$$z = -1{,}1635 + 1{,}6701 \cdot x + 0{,}0375 \cdot y$$

where: z – is the nickel content in the green plant;
x – nickel content in the studied soil;
y – nickel content in the root system.

The multiple CD (R^2 = 0.86) indicate a high correlation between these indicators. The relationship between the Co content in the vegetative mass and the metal content in the root system of the *Silphium Perfoliatum* L. and in the studied soil was noted (Fig. 5).

With the introduction of SS at a rate of 20– (variants 4–6) the Co content in the vegetative mass reached 0.89–1.01 mg/kg of plant, and in the root system it was respectively 0.56–0.71 mg/kg of plant, and in the studied soil – 2.52–2.63 mg/kg of soil. with the compost application at a rate of 20 – (variants 7–8), the Co content in the vegetative massreached 0.86–0.93 mg/kg of plant, the Cd content in the root system of *Silphium Perfoliatum* L., respectively, was 0.65–0.70 mg/kg of the plant, and in the studied soil – 2.46–2.55 mg/kg of soil (Lopushnyak et al. 2021, 2022).

$$z = 0.0982 - 0.0567 \cdot x + 1.4484 \cdot y$$

where: z – is the Co content in the green plant;
x – Co content in the studied soil;
y – Co content in the root system.

The multiple determination coefficient shows high correlation between these indicators for the SS introduction at a rate (R^2 = 0.78) indicate a high correlation between these indicators. The coefficient of biological absorption was used to determine the intensity of migration of heavy metals from the soil to plants. The highest coefficient of biological absorption of cadmium by *Silphium Perfoliatum* L. was noted for the introduction of SS, Nickel and Cobalt – for the introduction of

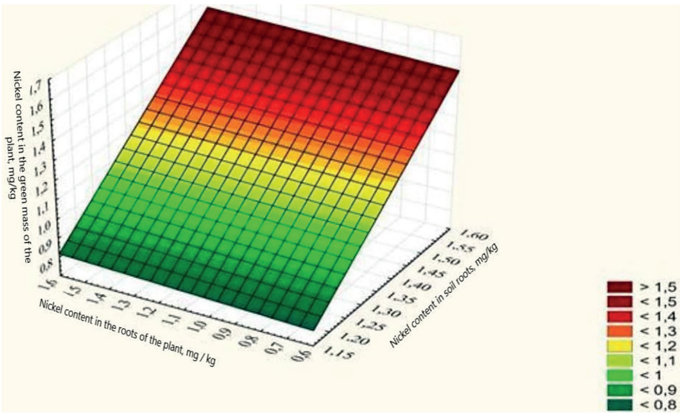

Figure 4. The dependence of the nickel content in the vegetative mass on the metal content in the roots of *Silphium Perfoliatum* L. and in the studied soil, the average for 2016–2020

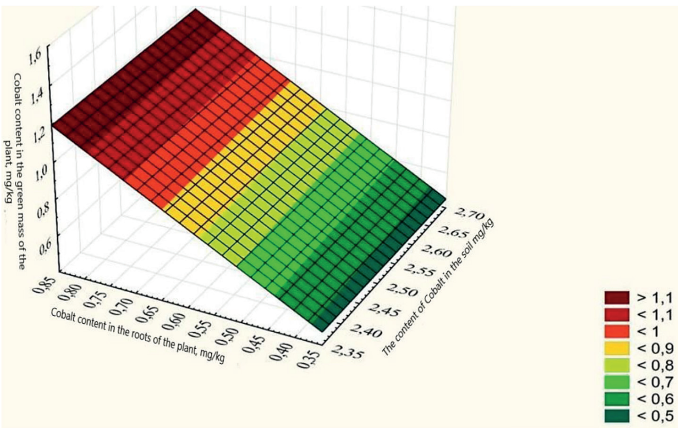

Figure 5. The cobalt content dependence in vegetative mass on metal content in the *Silphium Perfoliatum* L. roots in the studied soil, the average for 2016–2020

SS (variant 6), lead – in the control version and for the compost application at a rate (variant 7) (Table 3).

The lowest CBA of pollutants such as Cd, Ni, Pb *Silphium Perfoliatum* L. were noted for the addition of $N_{90}P_{90}K_{90}$ fertilizer to the soil, but cobalt – in the control version of the experiment. The coefficient of biological absorption of *Silphium Perfoliatum* L. increases in a number of elements: $Co^{2+} \rightarrow Ni^{2+} \rightarrow Pb^{2+} \rightarrow Cd^{2+}$. In all variants of the experiment, the elements of strong accumulation include nickel, lead and cobalt. The maximum lead biological absorption coefficients are characteristic of *Silphium Perfoliatum* L., For the option 4, Ni^{2+} – for the compost application for option 7, Co^{2+} – for option 7, Cd^{2+} – in the control version of the experiment. The lowest nickel and lead biological absorption coefficients were observed for the cultivation of *Silphium Perfoliatum* L. For the mineral fertilizer's application application $N_{90}P_{90}K_{90}$, Cd – for the SS application – 40 т/га + $N_{10}P_{14}K_{58}$, Co^{2+} – in the control version of the experiment (Lopushnyak et al. 2021, 2022).

According to the heavy metal's groups in the series by the biological absorption intensity, five gradations of biological accumulation of metals are used. The obtained results of heavy metals exceed 10n and more, so they belong to the first group and are the energy accumulation elements. the biological accumulation coefficients of the metals. The coefficients of biological accumulation of the studied elements by perforated sylph increase in a number of elements: Pb^{2+}. → Co^{2+} → Ni^{2+} → Cd^{2+} (Fig. 6).

The cobalt the content of the aboveground mass of the plant in the control variant was 0.61 mg/kg of plant, and the metal content in the ash was 32.1 mg/kg of plant. With the mineral fertilizer's application in the norm $N_{60–90}P_{60–90}K_{60–90}$ (variants 2 and 3) the Co content in the vegetative mass increased by 0.03–0.16 mg/kg of plant, respectively the investigated metal content in the ash – by 2.5–4.8 mg/kg of plant (Lopushnyak at al 2021, 2022).

With addition of SS is normal of 20 – (variants 4–6), the cobalt content was 0.88–1.00 mg/kg of plant in the ash it was respectively 39.1–45,3 mg/kg of plant (Fig. 6a). However, with the compost addition on the basis of SS a rafe of 20 – (variants 7 and 8) the leaf surface area of miscanthus plants was 17.6–19.9 cm^2/plant, which is 6.1–8.4 cm^2/plant more than the leaf area of plants of the control variant (Lopushnyak et al. 2021, 2022).

The cobalt content correlation dependence in the vegetative mass on the Co content in the plant ash of *Silphium Perfoliatum* L. can be:

$$y = 19.2084 + 24.1413 \cdot x$$

where: y –in the ash (cobalt);
x – in the aboveground mass (cobalt).

According to the correlation regression analysis results, this dependence caned be considered high, because the determination coefficient of determination is $R^2 = 0.80$, and the correlation coefficient r = 0.89.

With fertilizer addition on the SS (variants 4–6), the lead content was 0.74–0.97 mg/kg plants in green matter, and its content in the ash, respectively, 45.8–49.1 mg/kg of plant (Fig. 6b). However, with the compost addition on the SS (variants 7 and 8), the metal content in the vegetative mass is 0.78–0.91 mg/kg of plant, and the ash content is 44.8–45.6 mg/kg of plant. The Pb content correlation dependence in the vegetative mass on its content in the plant ash of plants of *Silphium Perfoliatum* L. can be (Lopushnyak et al. 2021, 2022):

Table 3. The biological absorption and accumulation coefficients of metals by *Silphium Perfoliatum* L. with the fertilizer's application based on SS average for 2016–2020

Variant	Biological absorption coefficients				Coefficient of biological accumulation			
	Cd	Ni	Pb	Co	Cd	Ni	Pb	Co
Without fertilizer (control)	123.4	2.8	3.3	1.5	376.1	57.5	10.5	13.4
$N_{60}P_{60}K_{60}$	116.6	2.7	3.2	1.6	309.6	56.2	10.3	14.2
$N_{90}P_{90}K_{90}$	108.2	2.7	3.1	1.7	210.7	54.0	9.8	14.9
Sewage sludge – 20 т/га + $N_{50}P_{52}K_{74}$	134.4	3.1	3.2	1.7	280.6	57.2	11.5	15.5
Sewage sludge – 30 т/га + $N_{30}P_{33}K_{66}$	121.6	3.1	3.2	1.8	216.2	56.3	11.2	16.1
Sewage sludge – 40 т/га + $N_{10}P_{14}K_{58}$	120.4	3.1	3.3	1.9	183.9	57.1	10.8	17.2
Compost (SS + straw (3: 1) 20 t/ha + $N_{50}P_{16}K_{67}$	129.7	3.0	3.3	1.7	326.5	57.7	10.8	15.6
Compost (SS + straw (3: 1) 30 t / ha + $N_{30}K_{55}$	120.1	3.1	3.2	1.8	223.5	56.6	10.3	15.9

$$y = 32.8687 + 15.6947 \cdot x$$

where: y –in ash (lead);
x –in the aboveground mass (lead).

With the compost application on the SS at a rale of 20 – (variants 7 and 8), the Cd content in the vegetative mass is 1.60–1.71 mg/kg of plant, and in the ash content is 94.7–95.1 mg/kg of plant. The Cd content correlation dependence of plants of *Silphium Perfoliatum* L. can be:

$$y = 41.4414 + 33.4766 \cdot x$$

where: y – in ash (Cd);
x – in the aboveground mass (Cd).

The nickel content correlation dependence in the vegetative mass out its content in the plant ash of plants of *Silphium Perfoliatum* L. can be (Fig. 6 e):

$$y = 43.76727 + 28.7522 \cdot x$$

where: y – in ash (nickel);
x – in the aboveground mass (nickel).

Thus, with increasing fertilizer application rates, the content of pollutants in the vegetative mass of the plant and in the ash of *Silphium Perfoliatum* L. increases.

CONCLUSIONS

The Cadmium content in the vegetative mass of *Silphium Perfoliatum* L. with the compost at a rate of and $N_{30}K_{55}$ is 1.71 mg/kg of plant (variant 8). The highest cadmium translocation coefficient in the system «soil-vegetative mass» of *Silphium Perfoliatum* L. was recorded for the introduction of SS at the rate of (variant 4) is equal to 4.12. The metal translocation coefficient in the system «soil- vegetative mass» and in the system «soil-root» increases in a number: $Cd^{2+} \rightarrow Ni^{2+} \rightarrow Co^{2+} \rightarrow Pb^{2+}$. That is, the lowest translocation coefficient is in the lead. However, the difference is that in the system «soil- root» the coefficient of translocation is higher by 2–3%, from the translocation of metals in the system «soil-vegetative mass».

The highest coefficient of biological absorption of cadmium by *Silphium Perfoliatum* L. was noted for the SS, Ni and Co – for the introduction

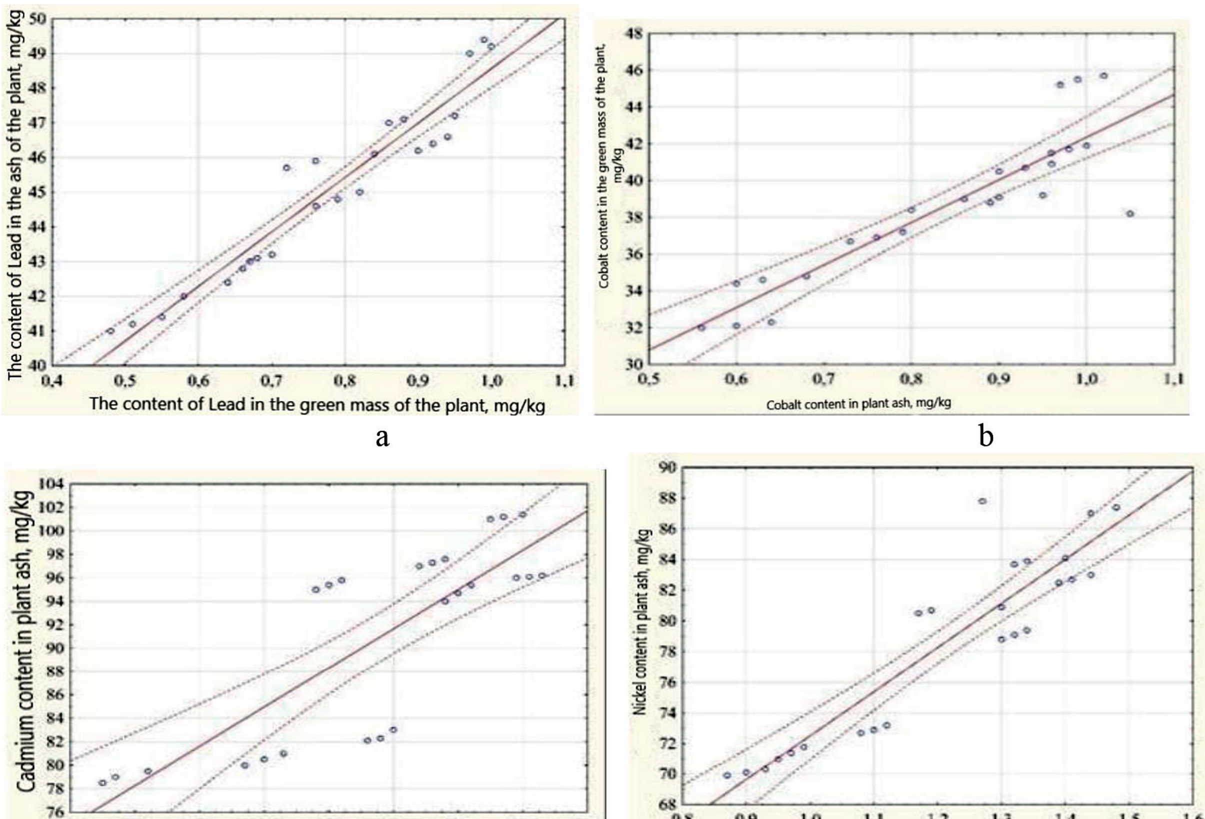

Figure 6. The correlation between the metals content (Co, Pb, Cd, Ni) in the vegetative mass from the content of metals in the ash of plants of *Silphium Perfoliatum* L., the average for 2016–2020

of SS at the rate of and $N_{10}P_{14}K_{58}$, Lead – in the control version and for the compost application at a rate of and $N_{50}P_{16}K_{67}$. According to the heavy metals groups in the series by the biological. Belong to the first gray and are the energy accumulation elements, because vegetation is able to selectively accumulate chemical elements. The biological accumulation coefficient of the HM by *Silphium Perfoliatum* L. increase in a number of elements: $Pb^{2+} \rightarrow Co^{2+} \rightarrow Ni^{2+} \rightarrow Cd^{2+}$.

REFERENCES

1. Ait Elallem, K., Sobeh, M., Boularbah, A., & Yasri, A. 2021. Chemically degraded soil rehabilitation process using medicinal and aromatic plants: Review. Environmental Science and Pollution Research, 28(1), 73–93. doi:10.1007/s11356–020–10742-y.
2. Avessalomova I.A. 1987. Geohimicheskie pokazateli pri izuchenii landshaftov [Geochemical indicators in the study of landscapes]. Izd-vo MGU.
3. Bekuzarova, S.A., Khatsaeva, F.M., Tebieva, D.I., Bekmurzov, A.D., Kebalova, L.A., & Gobeev, M.A. 2021. Soil toxicity reduction by phytoindicators. Paper presented at the IOP Conference Series: Earth and Environmental Science, 677(4) doi:10.1088/1755–1315/677/4/042100
4. Burt R. 2004. Soil survey laboratory methods manual. Soil Survey Investigations Report No. 42, Version 4.0, Natural Resources Conservation Service, United States Department of Agriculture.
5. Blanca Montalbán, Carmen Lobo, Juan Alonso, Araceli Pérez-Sanz. 2016. Metal(loid)s Uptake and Effects on the Growth of Helianthus tuberosus Cultivar-Clones Under Multi-Polluted Hydroponic Cultures. Clean – Soil, Air, Water, 44(10), 1368–1374. https://doi.org/10.1002/clen.201400630
6. Cui, X., Zhang, J., Wang, X., Pan, M., Lin, Q., Khan, K. Y., Chen, G. 2021. A review on the thermal treatment of heavy metal hyperaccumulator: Fates of heavy metals and generation of products. Journal of Hazardous Materials, 405 doi:10.1016/j.jhazmat.2020.123832.
7. Cho-Ruk K., J. Kurukote, P. Supprung, and S. Vetayasuporn. 2006. Perennial plants in the phytoremediation of lead-contaminated soils. Biotechnology, 5(1), 1–4.
8. Faruqui, N.I., Scott, C.A., Raschid-Sally, L. 2004. Confronting the realities of waste water in irrigated agriculture: lessons learned and recommendations. IDRC Books Free online. http://www.idrc.ca.
9. Eissa, M.A., Ghoneim, M.F., Elgharably, G.A., AbdElRazek, M. 2014. Phytoextraction of nickel, lead and cadmium from metals contaminated soils using different field crops and EDTA. World Applied Science Journal. 32, 1045–1052.
10. Eissa, M. A. 2014. Performance of river saltbush (Atriplex amnicola) grown on contaminated soils as affected by organic fertilization. World Applied Science Journal. 30, 1877–1881.
11. European Commission DG ENV. E3. 2002. Heavy Metals in Waste, Final Report Project ENV.E.3/ETU/2000/0058,http://ec.europa.eu/environment/waste/studies/pdf/heavy_metalsreport.pdf.
12. Gaur A. and A. Adholeya. 2004. Prospects of arbuscular mycorrhizal fungi in phytoremediation of heavy metal contaminated soils. Current Science, 86(4), 528–534.
13. Gamayunova V., Sydiakina O., Dvoretskyi V., Markovska O. (2021). Productivity of Spring Triticale under Conditions of the Southern Steppe of Ukraine. Ecological Engineering & Environmental Technology, 22(2), 104–112. https://doi.org/10.12912/27197050/133456
14. Ghazala M., Setsuko K. 2016. Toxicity of heavy metals and metal-containing nanoparticles on plants. Plant Gene, 2017, 11B, 247–254.
15. Ghori N.-H., Ghori T., Hayat M. Q., Imadi S. R., Gul A., Altay V. Ozturk M. 2019. Heavy metal stress and responses in plants. International Journal of Environmental Science and Technology, 16, 1807–1828
16. Ghosh, A.K., Bhatt, M.A., Agrawal, H.P. 2012. Effect of long-term application of treated sewage water on heavy metal accumulation in vegetables grown in northern India. Environ. Monit. Assess. 1842, 1025–1036.
17. Ilyas, N., Shoukat, U., Saeed, M., Akhtar, N., Yasmin, H., Khan, W., & Iqbal, S. 2021. Comparison of plant growth and remediation potential of pyrochar and thermal desorption for crude oil-contaminated soils. Scientific Reports, 11(1). doi:10.1038/s41598–021–82243-y.
18. Korsun S.G., Klymenko I. I., Bolokhovska V. A., Bolokhovskyy V.V. 2019. Translokatsiya vazhkykh metaliv u systemi «grunt-roslyna» za vapnuvannya ta vplyvu biolohichnykh preparativ [Translocation of heavy metals in the “soil-plant” system under liming and exposure to biological drugs. Agroecological monitoring, 1, 29–35. doi: https://doi.org/10.33730/2077–4893.1.2019.163245.
19. Lasat M. M. 2000. Phytoextraction of metals from contaminated soil: a review of plant/soil/metal interaction and assessment of pertinent agronomic issues. Journal of Hazardous Substance Research, 2(5), 1–25.
20. Lopushniak V., Hrytsuliak H., Kotsiubynsky A., Lopushniak H. 2021. Forecasting the Productivity of the Agrophytocenoses of the Miscanthus Giganteus for the Fertilization Based on the

Wastewater Sedimentation Using Artificial Neural Networks Ecological Engineering & Environmental Technology. 22(3), 11–19. https://doi.org/10.12912/27197050/134867

21. Lopushniak, V.I., Hrytsuliak, H.M. 2021. The models of the heavy metal accumulation of the multiple grain energy cultures for wastewater deposition on oil-polluted degraded soils. Ecological Engineering and Environmental Technology, 22(4), 1–13.
22. Lopushniak V., Tonkha O., Hrytsuliak H., Lopushniak H., Polutrenko M., Poberezhna L., Pikovska O., Tomasz Jakubowski, Kotsiubynsky Y., 2022. Productivity model of herbal bioenergy cultures depending on biometric indicators of overhead mass. Ecological Engineering & Environmental Technology 23(2), 162–172.
23. Rovira, J., Nadal, M., Schuhmacher, M., & Domingo, J.L. 2021. Environmental impact and human health risks of air pollutants near a large chemical/petrochemical complex: Case study in tarragona, spain. Science of the Total Environment, 787 doi:10.1016/j.scitotenv.2021.147550.
24. Rakhshaee R., M. Giahi, and A. Pourahmad. 2009. Studying effect of cell wall's carboxyl-carboxylate ratio change of Lemna minor to remove heavy metals from aqueous solution. Journal of Hazardous Materials, 163(1), 165–173.
25. Radu Sumalan, L., Muntean, C., Kostov, A., Kržanović, D., Noemi Jucsor, L., Sorin Ciulca, I., Cernicova-Buca, M. 2020. The cup plant (Silphium perfoliatum L.) – a viable solution for bioremediating soils polluted with heavy metals. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48(4), 2095–2113. doi:10.15835/48412160
26. Sarapulova, G.I. 2021. Study of the immobilizing capacity of humic substances in soils at oil contamination. Paper presented at the IOP Conference Series: Earth and Environmental Science, 720(1) doi:10.1088/1755–1315/720/1/012046
27. Shtangeeva, J., V.-P. Laiho, H. Kahelin, and G.R. Gobran. 2004. Phytoremediation of metal-contaminated soils. Symposia Papers Presented Before the Division of Environmental Chemistry. American Chemical Society, Anaheim, Calif, USA, , http://ersdprojects.science.doe.gov/workshop_pdfs/california_2004/p050.pdf.
28. Sivkov, Y. & Nikiforov, A. 2021. Study of oil-contaminated soils phytotoxicity during bioremediation activities. Journal of Ecological Engineering, 22(3), 67–72. doi:10.12911/22998993/132435
29. Soil quality. Determination of the content of mobile cadmium compounds in a buffer ammonium acetate extract with a pH of 4.8 by atomic absorption spectrophotometry: DSTU 4770.3: 2007. – Effective from 2009–01–01. К.: Держспоживстандарт України, 2009. 14 с. (National standard of Ukraine).
30. Soil quality. Determination of the content of mobile cobalt compounds in a buffer ammonium acetate extract with a pH of 4.8 by atomic absorption spectrophotometry: DSTU 4770.5: 2007. – Effective from 2009–01–01. К.: Держспоживстандарт України, 2009. 14 с. (National standard of Ukraine).
31. Soil quality. Determination of the content of mobile nickel compounds in a buffer ammonium acetate extract with a pH of 4.8 by atomic absorption spectrophotometry: DSTU 4770.7: 2007. Effective from 2009–01–01. К.: Держспоживстандарт України, 2009. 14 с. (National standard of Ukraine).
32. Soil quality. Determination of the content of mobile lead compounds in a buffer ammonium acetate extract with a pH of 4.8 by atomic absorption spectrophotometry: DSTU 4770.9: 2007. Effective from 2009–01–01. К.: Держспоживстандарт України, 2009. 14 с. (National standard of Ukraine).
33. Taketani, N.F., Taketani, R.G., Leite, S.G.F., Melo, I.S., de Lima-Rizzo, A.C., Andreote, F.D., & da Cunha, C.D. 2021. Application of extracellular polymers on soil communities exposed to oil and nickel contamination. Brazilian Journal of Microbiology, 52(2), 651–661. doi:10.1007/s42770–021–00428-z.
34. Tonkha O., A. Butenko, O. Bykova, Yu. Kravchenko, O. Pikovska, V. Kovalenko, I. Evpak, I. Masyk, E. Zakharchenko. 2021. Spatial Heterogeneity of Soil Silicon in Ukrainian Phaozems and Chernozems. Journal of Ecological Engineering, 22(2), 111–119.
35. Tonkha, O., Butenko, A., Bykova, O., Kravchenko, Y., Pikovska, O., Kovalenko, V., Zakharchenko, E. 2020. Spatial heterogeneity of soil silicon in ukrainian phaozems and chernozems. Journal of Ecological Engineering, 22(2), 111–119. doi:10.12911/22998993/130884
36. Tonkha, O.L., Sychevskyi, S.O., Pikovskaya, O.V., & Kovalenko, V.P. 2018. Modern approach in farming based on estimation of soil properties variability. Paper presented at the 12th International Scientific Conference «Monitoring of Geological Processes and Ecological Condition of the Environment», doi:10.3997/2214–4609.201803199
37. Vysotskaya, L.B., Kudoyarova, G.R., Arkhipova, T.N., Kuzina, E.V., Rafikova, G.F., Akhtyamova, Z.A., Loginov, O.N. 2021. The influence of the association of barley plants with petroleum degrading bacteria on the hormone content, growth and photosynthesis of barley plants grown in the oil-contaminated soil. Acta Physiologiae Plantarum, 43(4) doi:10.1007/s11738–021–03240–2.
38. Yakovleva, E.V. 2021. Biological monitoring experience of a natural and anthropogenic ecosystems ecological stability on the «spasskoye-lutovinovo» reserve territory with central forest-steppe gray forest soils. Paper presented at the IOP Conference Series: Earth and Environmental Science, 666(6) doi:10.1088/1755–1315/666/6/062028