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Removal of heavy metals by energy crops when grown on technologically contaminated soils

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ABSTRACT

The publication presents data on the removal of heavy metals by energy crops *Miscanthus giganteus L.* and *Phalaris arundinacea L.* when grown on technologically polluted soils. The yield of *Miscanthus giganteus* averaged 16.96 t/ha over the two years of research, and that of *Falaris arundinacea* – 4.38 t/ha, respectively. The nature of heavy metal accumulation by energy plants depended on the type of crop and its productivity during the years of cultivation. The concentration of all heavy metals in the phytomass of energy crops did not exceed the threshold limit value (TLV), except for zinc in miscanthus giganteus plants (by 9–11 mg/kg). Compared to the years of the study, in the second year of cultivation, the coefficient of heavy metal absorption by plants increased significantly compared to the first year due to an increase in the vegetative mass of plants. On average, in 2021–2023, the energy crops *Phalaris arundinacea* and *Miscanthus x giganteus* removed a significant amount of heavy metals from 1 ha of soil. It has been proven that energy crops such as *Phalaris arundinacea* and *Miscanthus x giganteus* contribute to the purification of technologically contaminated soils from heavy metals, and their products can be used further as biofuels and for other purposes, as the content of toxicants in their phytomass does not exceed the TLV.

Keywords: *Miscanthus x giganteus*, *Phalaris arundinacea*, heavy metals, toxicants, pesticides, oil products, TLV, phytoremediation. soil pollution, energy crops, soil remediation.

INTRODUCTION

Since anthropogenic pressure on soils leads to their degradation and a decrease in their soil grade, quality and productivity indicators (particle size distribution, humus, plant nutrients, water and thermal conditions), degree of erosion, salinity, acidity, salinity, pollution, etc., it is extremely important to keep the soil cover at least in a satisfactory condition to preserve the biosphere. This is especially true in urbanised areas, where the anthropogenic load on soils has long exceeded all permissible limits, posing a threat to human health and life (Rascio et al., 2011).

Heavy metals are absorbed from soils by plants, which then become food for more highly organised animals and humans (Tsytsyura et al., 2022; Romanchuk et al., 2022). Agricultural soils are increasingly contaminated with heavy metals due to industrialisation and increased anthropogenic activities (Ghous et al., 2022). Heavy metals are transmitted through trophic chains with a pronounced cumulative effect, and therefore their toxicity can manifest itself suddenly at certain links in trophic chains (Karmazynenko et al., 2014; Marques et al., 2009). For example, heavy metals and chemical pollutants, accumulating and moving along the soil-plant-animal-human food chain, affect various organs of animals and humans, causing diseases (Golets et al., 2009).

Heavy metals entering plants reduce yields and deteriorate their quality not only by toxicity, but also by preventing the supply of essential nutrients to plants. Metals such as chromium, nickel, copper, cadmium, mercury, and lead are inhibitors of phosphorus and potassium uptake into plants and their movement within the plant itself. Most heavy metals are accumulated in the root system of plants, less in the stems, and the least in the reproductive organs. This pattern is maintained with increasing concentrations of heavy metals in the soil (Ezaki et al., 2008; Técher et al., 2011; Nsanganwimana et al., 2014; Pidlisnyuk et al., 2018).

In Ukraine, this issue is particularly relevant now, when most of the country's land is exposed to environmental hazards as a result of military operations. The largest area of soils in Ukraine is contaminated with cobalt, molybdenum, and copper, with levels exceeding not only background values but also the TLV (Kulyk et al., 2019). In particular, according to researchers, the gross TLV of such heavy metals as lead is 5.4 times higher than the TLV, zinc – 3.9 times higher, cadmium – 1.4 times higher, manganese – 4.8 times higher, copper – 4.6 times higher, and iron – 1.2 times higher in the territory of military operations (Zaitsev et al., 2022).

Scientists all over the world are studying the issues of soil phytotherapy using energy crops, namely Poland and Romania (Nsanganwimana et al, 2014; 2015), France, the USA (Bourgeois et al., 2015; Nurzhanova, Pidlisnyuk, Sailoukhanuli, et al., 2015; Pidlisnyuk et al., 2018), Belgium (Meers et al., 2007; Meers et al., 2010); Portugal and Brazil (de Abreu et al., 2012); India (Pandey et al., 2015). The selected crops should restore contaminated areas, improve soil quality, create an aesthetically pleasing landscape and sequester carbon. In this way, there is a potential link between energy crops and phytoremediation of contaminated land (Witters et al., 2012).

The maximum phytoremediation effect on contaminated lands is observed in fast-growing woody plant species, while very little attention is paid to the use of grass energy crops (Técher et al., 2011), and only a few sources describe the use of second-generation perennial biofuel crops for phytoremediation of contaminated lands (Hromádko et al., 2010).

The advantages of using biological methods of soil remediation are as follows: environmental friendliness and safety of biological remediation methods, minimal disturbance of the physical and chemical composition of soils; their use does not require significant expenditure of material resources; high efficiency at low concentrations of pollutants. Growing energy crops as a means of phytoremediation on contaminated and degraded soils is a promising area. This will not only help reduce the level of degradation but also increase the agronomic value of these soils. Phytoremediation and metal sorption methods can be used together to complement each other to enhance soil remediation (Petrushka et al., 2024; Samokhvalova et al., 2014). The list of such plants should be supplemented with perennial energy crops, taking into account the absorption capacity of their root system (Kulyk et al., 2019).

Scientific studies conducted by foreign scientists indicate the presence of a certain group of plants, the so-called hyperaccumulators of heavy metals (Alasmary et al., 2021; Chernysh et al., 2024). Perennial energy crops are able to quickly form aboveground phytomass and form a powerful root system, which allows them to accumulate heavy metals from the soil and become new and important plants for phytoremediation. At the same time, energy crops are placed in accordance with agroclimatic zoning, taking into account the reaction of plants to growing conditions and using a scheme for cleaning soils from heavy metals. The nature of the accumulation of heavy metals and toxicants in plants depends on the type of crop and the characteristics of the toxicant. The protective role of the root system in the accumulation of metals by the aboveground mass of plants has been established: the roots are the most resistant to lead, nickel, and chromium (Kulyk et al., 2019). Restoration of the functional and ecosystem properties of contaminated land through phytoremediation will allow it to be returned to agricultural use.

At the end of the growing season, the aboveground vegetative mass of these plants may be subject to appropriate processing, which is an additional source of non-ferrous metals, or biofuel production for energy purposes (Kulyk et al., 2019). Therefore, when planning phytoremediation measures, it is necessary to take into account both the type of pollution and the possibility of further use of biomass. This will not only allow for effective soil clean-up, but also provide additional economic benefits and minimise risks to public health (Datsko et al., 2024).

At the same time, modern scientific publications do not fully cover the peculiarities of heavy metal accumulation by energy crops, the mechanism of pollutant transfer from soil to plants; the model of soil purification from pollutants needs to be clarified, which is why our research in this area is relevant.

MATERIALS AND METHODS

The study was conducted during 2021–2023 within the framework of the CERESiS (ContaminatEd Land Remediation through Energy crops for Soil improvement to liquid biofuels) H2020 Project (GA 101006717) in an experiment that was established in 2021 in a stationary experiment in the Polissya region of Ukraine. To study the concentration of heavy metals in the phytomass of energy crops, we have established experimental sites of energy plants Miscanthus x giganteus and Phalaris arundinacea on soils contaminated with oil products (site 1) and organic pesticides (site 2).

The soil of the experimental sites is light grey podzolised gleyish, characterised by a neutral reaction of the medium, a high indicator of the sum of absorbed bases, very low humus and phosphorus content, very high exchangeable potassium, easily hydrolysed nitrogen, high content of mobile sulphur, and increased exchangeable calcium.

The experiment was laid out in 3 replications, with replications arranged in one row. The total area of the site is 540 m^2, the area of the sowing site is 135 m^2, the accounting site is 100 m^2. According to the scheme of the experiment, we applied the recommended norms of phosphorus-potassium fertilisers - superphosphate P_2O_5 – 18.4 % and potassium magnesium (K_2O – 40.2 %), nitrogen fertilisers - ammonium nitrate (N 34.4 %). Phalaris arundinacea plants were systematically watered, as it is a very moisture-loving plant.

Laboratory studies of soil and plants were carried out in accordance with current methods and DSTU in a certified laboratory. We analysed the soil and biomass of Miscanthus x giganteus and Phalaris arundinacea plants from experimental sites 1 and 2 for heavy metals: Cd, Zn, V, Pb, Cu, Ni, Sb, Mn, As, Th, Hg, Sn, Cr, Co. Calculation formula for determining the coefficient of accumulation of heavy metals from soil to plants: accumulation coefficient (AC) = metal content in vegetation, (mg/kg/)/ metal content in soil, (mg/kg).

RESULTS AND DISCUSSION

Crop yields are the main indicator of their productivity. The yield of energy crops directly depends on climatic, soil and other conditions, the main of which is maintaining the balance of nutrients through the application of mineral fertilisers.

However, as other scientists point out, too high concentrations of pollutants in the soil can lead to a decrease in the productivity of the vegetative mass of energy crops (Kayama, 2001; Pidlisnyuk et al., 2014).

In our research, we determined the yield of vegetative biomass of energy crops to enable further calculations of the removal of heavy metals and toxicants from the soil.

Comparing the yield of green mass of energy crops by years of cultivation, it was found that the largest increases were in 2023, due to the fact that these crops maximise their vegetative mass in 3–5 years of vegetation (Table 1).

It was found that the plants of Miscanthus giganteus and common reed increased the greatest vegetative mass in 2023. The yield of miscanthus giganteus was 17.12 t/ha and 18.7, which is 2–22 % more compared to the first year of vegetation.

Table 1. Energy crop yields in 2021–2023, t/ha

Years of research	Phalaris arundinacea		Miscanthus x giganteus	
	Site No. 1 (oil contamination)	Site No. 2 (contaminated with organic pesticides)	Site No. 1 (oil contamination)	Site No. 2 (contaminated with organic pesticides)
2021–2022	4.06	3.8	16.7	15.3
2022–2023	4.62	5.03	17.12	18.7
Average	4.34	4.42	16.91	17.0

Note: developed by the authors.

The yields of common reed were 4.62 and 5.03 t/ha, respectively, which is 14–32% more than in 2022. The largest increase in green mass was observed when growing miscanthus giganteus and common reed on a site contaminated with organic pesticides, and the smallest increase was observed when growing on a site contaminated with oil products.

The results of our research showed that the content of toxicants in the soil decreased with each year of energy crops cultivation (Table 2). In sites after cultivation of *Miscanthus x giganteus*, the content of heavy metals in the soil was much lower than after Phalaris arundinacea, which is explained by the much larger vegetative mass of plants (Romantschuk et al., 2024).

This is confirmed by other scientists who consider phytoremediation using the second-generation bioenergy of *Miscanthus x giganteus* to be an effective method of soil remediation from heavy metals compared to other energy crops (Nurzhanova et al., 2019). It has been established that energy crops (switchgrass and miscanthus) are hyperaccumulators, actively absorbing heavy metals and partially accumulating them in their underground and aboveground parts. In particular, giant miscanthus (*Miscanthus giganteus*) provides higher yields than rod millet (Panicum virgatum), although the latter species provides lower dry matter content, has a higher accumulation of heavy metals in plant phytomass, but the maximum permissible concentration is lower than that regulated by the standards (Kulyk et al., 2019). In particular, in our studies on the site contaminated with oil products, the copper content of Phalaris arundinacea decreased by 1.734 μ/kg, while that of Miscanthus x giganteus decreased by 3.353 mg/kg; manganese by 8.02 mg/kg and 11.04 mg/kg, respectively; lead by 10.808 mg/kg and 12.744 mg/kg; and cobalt by 2.0 mg/kg and 3.75 mg/kg. The same trend is observed for all elements in the second site, which is contaminated with pesticides. Energy crops remove the most manganese, zinc, lead, cobalt, and chromium from the soil.

Scientists have established a positive correlation between the content of mobile heavy metal compounds in soil and their accumulation in plants and consider it necessary to compare their content in soils and in the vegetative mass of plants. Various studies (Ezaki et al., 2008; Técher et al., 2011; Nsanganwimana et al., 2014; Pidlisnyuk et al., 2018) have reported the deposition of some heavy metals (As, Sn, Cd, Cr, Cu, Ni, Pb, Zn and Al) by miscanthus, which usually accumulated most in the lower part of plants, and in stunted species - in stems and leaves (Nsanganwimana et al., 2015). Comparing the content of

Table 2. Changes in the gross content of heavy metals in the soil when growing energy crops, mg/kg (2021–2023)

No. s/n	Element	Before laying	TLV	The site is contaminated with oil products				Before laying	The site is contaminated with pesticides			
				Phalaris arundinacea	Removal	Miscanthus x giganteus	Removal		Phalaris arundinacea	Removal	Miscanthus x giganteus	Removal
1	Cu	10.188	-	8.454	1.734	6.835	3.353	14.63	12.133	2.497	11.645	2.985
2	Mn	84.42	1500	76.4	8.02	73.38	11.04	101	84.42	16.58	79.23	21.77
3	Zn	42.34	-	35.465	6.875	34.779	7.561	50.86	44.862	5.998	45.749	5.111
4	Pb	17.49	32	6.682	10.808	4.746	12.744	22.75	9.406	13.344	7.459	15.291
5	Co	5.75	-	3.75	2.0	2	3.75	7.79	5.908	1.882	3.18	4.61
6	Cd	1.43	1.5	1.299	0.131	1.237	0.193	1.89	1.703	0.187	1.578	0.312
7	Cr	27	-	24.08	2.92	23.06	3.94	42.5	39.54	2.96	40.043	2.457
8	Ni	4.01	-	3.89	0.12	3.32	0.69	3.86	3.75	0.11	3.701	0.159
9	As	0.09	2.0	0.072	0.018	0.081	0.009	0.089	0.075	0.014	0.078	0.011
10	V	6.08	150	5.77	0.31	5.65	0.43	5.03	4.95	0.08	4.851	0.179
11	Sb	172.11	4.5	112.11	60	102.5	69.61	161.15	128.15	33	98.6	62.55
12	Sn	131.2	-	111.5	19.7	105.1	26.1	134.32	95.3	39.02	82.8	51.52
13	Hg	0.426	2.1	0.262	0.164	0.224	0.202	0.503	0.256	0.247	0.23	0.273

Note: developed by the authors.

heavy metals in the phytomass of energy crops in our studies, their concentration in the phytomass of plants of the second year increased significantly compared to the first year, i.e., they were absorbed more from the soil (Figs. 1, 2).

When growing common reed on the site contaminated with oil products, the lead content increased by 0.45 mg/kg, on the site contaminated with pesticides by 0.37 mg/kg; when growing miscanthus by 0.34 and 0.32 mg/kg, respectively, on the sites. The lowest lead content was observed in the plants of common reed in the 3rd year of cultivation (1.81 and 1.67 mg/kg). As for Miscanthus giganteus, the content of the toxicant in the third year of cultivation varied from 1.38 to 1.47 mg/kg, respectively, however, these values are significantly lower than the TLV.

The concentration of cadmium in energy crop plants varied from 0.094 mg/kg to 0.211 mg/kg, and the lowest concentration of cadmium was noted in the phytomass of miscanthus giganteus of the first cut (0.094–0.106 mg/kg), and the highest concentration was in the plants of common reed (0.198-0.211 mg/kg) at the TLV of 0.3 mg/kg.

As for such a toxicant as copper, its content in the phytomass of energy crops when grown on contaminated soils was also significantly lower than the TLV and was in the range of 2.73–3.17 mg/kg for reeds and 8.49–9.89 mg/kg for miscanthus by site, respectively.

The zinc concentration was the highest in miscanthus giganteus plants – it varied within 50.2–61.9 mg/kg, which significantly exceeded the TLV.

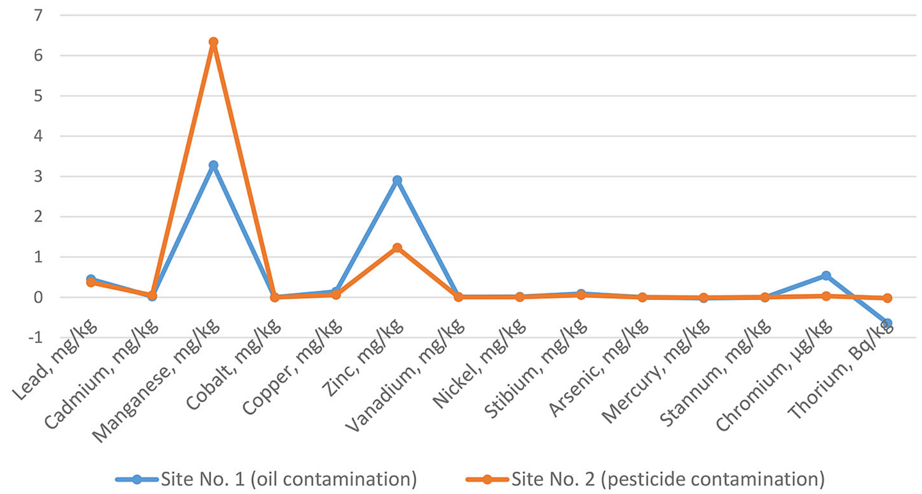

Figure 1. Changes in the content of heavy metals in common reed plants (*Phalaris arundinacea*) for 2021–2023 research years

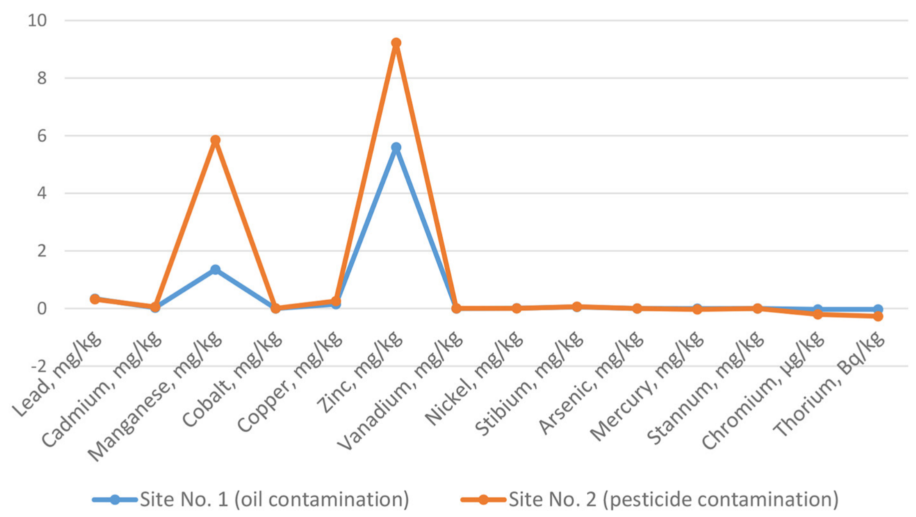

Figure 2. Changes in the content of heavy metals in miscanthus giganteus plants (*Miscanthus x giganteus*) for 2021–2023 research years

The increased content of heavy metals in plants depends on the phenophase of plant development, with the highest amount of heavy metals accumulating in plants at the end of their growth period. The removal of heavy metals by plants is not always related to their amount in the soil, because the more organic matter in the soil, the more it adsorbs metals, forming compounds such as chelates. The transfer of metals to plants and their absorption rate are generally determined by the content of their mobile forms, the ratio of metals in the soil, the manifestation of ion antagonism processes, etc.

The study of Czech scientists on the peculiarities of the process of heavy metal absorption by Miscanthus giganteus indicates that it significantly depended on the type of soil. According to the bioconcentration coefficient, the absorption of abiogenic elements Cr and Pb was dominant in plant roots in different soils, while Ni was not detected in any plant tissue. The behaviour of biogenic elements (Mn, Cu, Zn) and their analogues (Sr) was different (Nebeská et al., 2019).

In our research, we annually determined the content of heavy metals in the soil and vegetative mass of energy crops, and calculated the coefficient of their accumulation in the phytomass of plants. Again, we observe a significantly higher content of toxicants in Miscanthus x giganteus plants than in Phalaris arundinacea for all years of the study. In the first year of cultivation, the greatest difference is observed in the transition of heavy metals such as copper - the accumulation coefficient of miscanthus was 0.47–0.55 mg/kg higher than that of reeds, manganese - 0.166–0.19 mg/kg and zinc - 0.19-0.46 mg/kg. For such elements as chromium, nickel, vanadium, and stibium, the accumulation coefficients by energy crops did not differ significantly (Table 3). However, such elements as lead, cadmium, arsenic, stannum and mercury were absorbed by reed plants more than by miscanthus plants.

In the second year (Table 4) of cultivation, the accumulation coefficient of miscanthus was higher than that of reeds: copper by 0.61–0.91 mg/kg, manganese – 0.20–0.21 mg/kg, zinc – 0.36–0.66 mg/kg, lead – 0.007–0.0039 mg/kg, cobalt – 0.0014–0.0018 mg/kg, nickel – 0.003 mg/kg, arsenic – 0.12–0.13 mg/kg, vanadium – 0.001 mg/kg, stibium – 0.0004–0.0006 mg/kg, and stannum – 0.0002-0.00003 mg/kg. However, reed canarygrass plants absorbed such toxicants as cadmium – by 0.031–0.042 mg/kg, chromium – 0.003–0.005 mg/kg and mercury – 0.112–0.241 mg/kg more than miscanthus plants.

The accumulation of such heavy metals as Cd, Cu, Fe, Co, Ni and Pb in the organs of reed canary grass has been noted by other scientists, which allows them to be removed from the cycle of elements, contributing not only to the purification but also to the restoration of the ecological potential of the ecosystems in which they grow. Thus, the

Table 3. Indicators of the intensity of heavy metal migration in the soil-plant link, 2021–2022

No. s/n	Element	Gross content in soil, mg/kg		Content in Phalaris arundinacea plants, mg/kg		*AC		Content in plants of Miscanthus x giganteus, mg/kg		**AC	
		**№1	***№2	**№1	***№2	**№1	***№2	**№1	***№2	**№1	***№2
1.	Cu	10.188	14.63	3.03	2.73	0.297	0.187	8.63	9.63	0.847	0.658
2.	Mn	84.42	101	11.82	10	0.140	0.099	28.55	26.65	0.338	0.264
3.	Zn	42.34	50.86	36.9	40.77	0.872	0.802	56.3	50.2	1.330	0.987
4.	Pb	17.49	22.75	1.36	1.3	0.078	0.057	1.13	1.06	0.065	0.047
5.	Co	5.75	7.79	0.0018	0.0016	0.0003	0.0002	0.0021	0.0021	0.0004	0.0003
6.	Cd	1.43	1.89	0.176	0.163	0.123	0.086	0.106	0.094	0.074	0.050
7.	Cr	27	42.5	1.21	1.74	0.045	0.041	1.55	1.82	0.057	0.043
8.	Ni	4.01	3.86	0.021	0.023	0.005	0.006	0.027	0.025	0.007	0.006
9.	As	0.09	0.089	0.0031	0.0037	0.034	0.042	0.003	0.0053	0.033	0.060
10.	V	6.08	5.03	0.011	0.01	0.0018	0.0020	0.012	0.011	0.0020	0.0022
11.	Sb	172.11	161.15	0.1	0.12	0.0006	0.0007	0.16	0.13	0.0009	0.0008
12.	Sn	131.2	134.32	0.006	0.003	0.00005	0.00002	0.0032	0.0035	0.00002	0.00003
13.	Hg	0.426	0.503	0.15	0.17	0.352	0.338	0.09	0.12	0.211	0.239

Note: **AC is the accumulation coefficient; **No. 1 – the site is contaminated with oil products; ***No. 2 – the site is contaminated with pesticides.

Table 4. Indicators of the intensity of heavy metal migration in the soil-plant link, 2022–2023

No. s/n	Element	Gross content in soil, mg/kg		Content in Phalaris arundinacea plants, mg/kg		*AC		Gross content in soil, mg/kg		Content in plants of Miscanthus x giganteus, mg/kg		*AC	
		**№1	***№2	**№1	***№2	**№1	***№2	**№1	***№2	**№1	***№2	**№1	***№2
1.	Cu	8.454	12.133	3.17	2.79	0.375	0.230	6.835	11.645	8.78	9.89	1.285	0.849
2.	Mn	76.4	84.42	15.1	16.34	0.198	0.194	73.38	79.23	29.9	32.5	0.407	0.410
3.	Zn	35.465	44.862	39.81	42	1.123	0.936	34.779	45.749	61.9	59.43	1.780	1.299
4.	Pb	6.682	9.406	1.81	1.67	0.271	0.178	4.746	7.459	1.47	1.38	0.310	0.185
5.	Co	3.75	5.908	0.0024	0.0023	0.0006	0.0004	2	3.18	0.0048	0.0058	0.0024	0.0018
6.	Cd	1.299	1.703	0.198	0.211	0.152	0.124	1.237	1.578	0.136	0.147	0.110	0.093
7.	Cr	24.08	39.54	1.75	1.77	0.073	0.045	23.06	40.043	1.52	1.62	0.066	0.040
8.	Ni	3.89	3.75	0.032	0.03	0.008	0.008	3.32	3.701	0.036	0.03	0.011	0.008
9.	As	0.072	0.075	0.003	0.0035	0.042	0.047	0.081	0.078	0.0044	0.0047	0.054	0.060
10.	V	5.77	4.95	0.0184	0.0149	0.003	0.003	5.65	4.851	0.0152	0.0176	0.003	0.004
11.	Sb	112.11	128.15	0.188	0.179	0.0017	0.0014	102.5	98.6	0.214	0.195	0.0021	0.0020
12.	Sn	111.5	95.3	0.0037	0.0039	0.00003	0.00004	105.1	82.8	0.0048	0.0056	0.00005	0.00007
13.	Hg	0.262	0.256	0.131	0.163	0.500	0.637	0.224	0.23	0.087	0.091	0.388	0.396

Note: **AC is the accumulation coefficient; **No. 1 – the site is contaminated with oil products; ***No. 2 – the site is contaminated with pesticides**.**

discovery of the phenomenon of heavy metal hyperaccumulation in reed plants, their large plant mass and high growth density prove the feasibility of using them as effective phytoremediation agents near ditches and rivers. This will reduce the leakage of heavy metals into the groundwater of the surrounding areas and rivers, which will reduce the anthropogenic load on the environment (Baranov et al., 2012; Kipnis et al., 2012).

Also, in the second year of cultivation, the coefficient of absorption of heavy metals by plants increased significantly compared to the first year due to an increase in the vegetative mass of plants. In particular, reed plants absorbed copper by 22–26%, manganese by 41–95%, zinc by 16–28%, lead by 3–3.5 times, cobalt by 2 times, cadmium by 23–44%, chromium by 9–62%, nickel by 33–60%, arsenic by 11–23%, vanadium by 50–66%, stibium and stannum by 2 times, and mercury by 42–88%. The same trend was observed in miscanthus plants: copper by 29–51%, manganese by 20–55%, zinc by 31–33%, lead by 4–4.8 times, cobalt by 6 times, cadmium by 48–86%, chromium by 15%, nickel by 33–57%, arsenic by 63%, vanadium by 50–81%, stibium and stannum by 2.3–2.5 times, and mercury by 65–83%.

The vast majority of scientists confirm phytoremediation of soils by growing energy crops. It has been established that regardless of the type of energy crop, the intensity of heavy metal transfer in the soil-plant system is as follows: Cd → Cu → Zn → Pb → Co (Kulik, 2016).

According to our research, we calculated the removal of heavy metals by energy crops for 2021–2023. It was found that Phalaris arundinacea was removed with the harvest from 1 ha of soil: Cu – 10–12 kg; Mn – 38–47 kg; Zn – 149–154 kg; Pb – 4.9–5.5 kg; Co – 6–7 g; Cd – 0.6–0.7 kg; Cr – 4.9–6.6 kg; Ni – 87–85 g; As – 13–14 g; V – 38–45 g; Sb – 406–456 g; Sn – 11–24 g; Hg – 609–646 g (Table 5).

Miscanthus x giganteus, respectively, yielded 11–14 times more Cu per 1 ha of soil; 9–10 times more Mn; 5–6 times more Zn; 3.2–3.4 times more Pb; 5–5.3 times more Co; 2.3–2.5 times more Cd; 4.2–5.2 times more Cr; 4.4–5.3 times more Ni; 3.8–5.8 times more As; 4.4 times more V; 4.4 times more Sb; 4.4–6.5 times more Sn; 2.2–4.9 times more Hg. Scientists have shown that the uptake of Zn and Pb by young plants of Miscanthus x giganteus increases in proportion to their concentration in the soil (Alasmary et al., 2021).

In the second year of cultivation, the removal of toxicants from the soil increased, Phalaris arundinacea removed 19–35% more Cu; 45–116% – Mn; 22–36% – Zn; 51–70% – Pb with the harvest from 1 ha of soil; 58–93% – Co; 27–71% – Cd; 34–64% – Cr; 73–74% – Ni; 7–28% – As; 2 times more V and Sb; 80% more Sn on the pesticide-contaminated site; 26 % more Hg on the

Table 5. Removal of heavy metals by energy crops, 2021–2022

No. s/n	Culture	Site number	Yield, t/ha	Output with harvest from 1 ha, kg												
				Cu	Mn	Zn	Pb	Co	Cd	Cr	Ni	As	V	Sb	Sn	Hg
1.	Phalaris arundinacea	*№1	4.06	12.302	47.989	149.814	5.522	0.007	0.715	4.913	0.085	0.013	0.045	0.406	0.024	0.609
		**№2	3.8	10.374	38.000	154.926	4.940	0.006	0.619	6.612	0.087	0.014	0.038	0.456	0.011	0.646
2.	Miscanthus x giganteuS	*№1	16.7	144.121	476.785	940.210	18.871	0.035	1.770	25.885	0.451	0.050	0.200	2.672	0.053	1.503
		**№2	15.3	147.339	407.745	768.060	16.218	0.032	1.438	27.846	0.383	0.081	0.168	1.989	0.054	1.836

Note: No. 1 – the site is contaminated with oil products; **No. 2 – the site is contaminated with pesticides.

Table 6. Removal of heavy metals by energy crops, 2022–2023

No. s/n	Culture	Site number	Yield, t/ha	Output with harvest from 1 ha, kg												
				Cu	Mn	Zn	Pb	Co	Cd	Cr	Ni	As	V	Sb	Sn	Hg
1.	Phalaris arundinacea	*№1	4.62	14.645	69.762	183.922	8.362	0.0111	0.915	8.085	0.148	0.014	0.085	0.859	0.017	0.605
		**№2	5.03	14.0334	82.190	211.260	8.400	0.0116	1.061	8.903	0.151	0.018	0.075	0.090	0.020	0.820
2.	Miscanthus x giganteus	№1	17.12	150.314	511.888	1059.72	25.16	0.082	2.328	26.02	0.616	0.075	0.260	3.663	0.082	1.489
		№2	18.7	184.943	607.75	1111.34	25.80	0.108	2.749	30.29	0.561	0.088	0.329	3.647	0.105	1.702

Note: *No. 1 – the site is contaminated with oil products; **No. 2 – the site is contaminated with pesticides.

pesticide-contaminated site (Table 6). *Miscanthus x giganteus* yielded 4–25% more Cu, 7–49% more Mn, 12–44% more Zn, 33–59% more Pb, 2.3–3.3 times more Co, 31–91% more Cd, 8% more Cr, 36–46% more Ni, 8–505% more As, 30–95% more V, 54–94% more Sb, and only Hg removal was at the level of the first year of cultivation. The results of other scientists confirm the high potential of Miscanthus sp. for phytostabilisation of heavy metal contaminated areas and their transfer in the soil-plant link and improvement of soil condition (Alasmary et al., 2021).

Thus, our research has shown that the nature of heavy metal accumulation by plants depended on the type of crop and its productivity. It has been clearly proven that such energy crops as Phalaris arundinacea and *Miscanthus x giganteus* contribute to the purification of technologically pollutedsoils from heavy metals, and their products can be used in the future as biofuels and for other technical purposes, since the content of toxicants in their phytomass does not exceed the TLV, except for zinc. It has been proven that the use of hyperaccumulator plants can significantly reduce the concentration of heavy metals in soils, which will help restore biodiversity and improve the ecological condition of the affected areas (Romanchuk et al., 2021; Datsko et al., 2024).

Energy crops have a significant potential for phytostabilisation of heavy metals on contaminated land, preventing further migration of pollutants into groundwater or air (Fijalkowski et al., 2018).

CONCLUSIONS

According to the results of our research, it was found that when growing *Phalaris arundinacea* and *Miscanthus x giganteus* on technologically pollutedsoils, their largest vegetative mass was in the second year of cultivation and amounted to 17.12 t/ha and 18.7 t/ha, which is 2–22% more than in the first year, and common reed – 4.62 t/ha and 5.03 t/ha, which is 14–32% more than in 2022.

The nature of accumulation of heavy metals by energy plants depended on the type of crop and its productivity during the years of cultivation. Common reed plants had the following tendency in terms of heavy metal accumulation coefficient: Sn→Co→Sb→V→Ni→As→Cr→Pb→Cd→Mn→Cu→Hg→Zn. Plants of Miscanthus giganteus: Sn→Co→Sb→V→Ni→As→Cr→Pb→Cd→Hg→Mn→Cu→Zn.

The concentration of all heavy metals in the phytomass of energy plants did not exceed the TLV, except for zinc in miscanthus giganteus plants (from 50.2-61.9 mg/kg).

During the first year of the study, a significantly higher content of such toxicants as copper, manganese, and zinc was observed in *Miscanthus x giganteus* plants than in Phalaris arundinacea. For such elements as chromium, nickel, vanadium, and stibium, the accumulation coefficients of energy plants did not differ significantly. And such elements as lead, cadmium, arsenic, stannum and mercury were absorbed by reed plants more than by miscanthus plants. In the second year of cultivation, the coefficient of accumulation of copper, zinc, lead, cobalt, nickel, arsenic, vanadium, stibium, and stannum increased. However, reed plants absorbed such toxicants as cadmium, chromium and mercury more than miscanthus plants.

In the second year of cultivation, the coefficient of heavy metal uptake by plants increased significantly compared to the first year due to an increase in the vegetative mass of plants. On average, in 2021-2023, the removal of heavy metals by energy crops was as follows: Phalaris arundinacea removed with the harvest from 1 ha of soil: Cu – 12.8 kg; Mn – 59.5 kg; Zn – 175 kg; Pb – 6.8 kg; Co – 9 g; Cd – 0.8 kg; Cr – 7.1 kg; Ni – 120 g; As – 15 g; V – 61 g; Sb – 658 g; Sn – 18 g; Hg – 670 g. Miscanthus x giganteus, respectively, yielded 12 times more Cu per 1 ha of soil; 8.4 times more Mn; 5.5 times more Zn; 3 times more Pb; 7 times more Co; 2.5 times more Cd; 3.9 times more Cr; 4.3 times more Ni; 5 times more As; 3.9 times more V; 4.6 times more Sb; 4 times more Sn; 2.4 times more Hg.

It was found that the nature of heavy metal accumulation by plants depended on the type of crop and its productivity. Thus, the concentration of heavy metals in energy crops grown in contaminated areas increased with the year of cultivation. It has been unequivocally proven that energy crops such as Phalaris arundinacea and *Miscanthus x giganteus* contribute to the purification of technologically polluted soils from heavy metals, and their products can be used in the future as biofuels and for other technical purposes, since the content of toxicants in their phytomass does not exceed the TLV, except for a slight excess of zinc.

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