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Phytoremediation of Soils by Cultivation *Miscanthus x Giganteus* L. and *Phalaris arundinacea* L.

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ABSTRACT

Restoring soil fertility and protecting it from pollution are complex scientific tasks of our time that require a set of physical, chemical and biological measures. An important theoretical and applied aspect is the development of new remediation methods to reduce soil degradation processes under the influence of chemical pollution. The publication analyzes the ecological features of the energy crops *Miscanthus giganteus* L. and *Phalaris arundinacea* L. as phytoremediation agents of soils contaminated with heavy metals, pesticides, and oil products. The content of toxicants in contaminated soils as a result of energy crops cultivation has significantly decreased, in particular, the content of mobile forms and the mass fraction of heavy metals. The greatest decrease was observed in the content of mobile forms of chromium: in the area contaminated with petroleum products by 0.55 mg/kg when growing reeds and by 1.06 mg/kg when growing miscanthus, and in the area contaminated with pesticides by 3.65 and 5.25 mg/kg, respectively. The gross stibium content decreased in the area contaminated with oil products by 60 mg/kg when growing reeds and by 69.61 mg/kg of soil when growing miscanthus, and by 65.68 and 78.35 mg/kg in the area contaminated with pesticides. The concentration of cadmium in the studied plots where energy crops were grown decreased in the range of 0.131–0.193 mg/kg when growing *Phalaris arundinacea* L. and by 0.187–0.312 mg/kg when growing *Miscanthus giganteus* L., respectively. The content of organic pollutants was also significantly reduced.

Keywords: heavy metals, phytoremediation, organic pollutants, *Phalaris arundinacea*, *Miscanthus x giganteus*, oil products, toxicants.

INTRODUCTION

Man-made environmental pollution is global in nature. Human economic activity has led to land degradation and contamination with oil products, pesticides, radionuclides and heavy metals, which are among the most harmful chemical pollutants for the environment. They migrate through trophic chains with a pronounced cumulative effect, which is why their toxicity can manifest itself suddenly at certain links in the trophic chains. Non-agricultural lands include contaminated soils near mining and metallurgical facilities; quarries, solid waste landfills and other marginal areas characterized by exceeding the MPCs for inorganic (heavy metals: Pb, Cr, Al, Zn, Ni, etc.) and organic (polycyclic aromatic hydrocarbons, pyrene, phenanthrene, polyphenolic compounds, etc.) compounds (Ridej et al., 2009; Samokhvalova 2014; Moubasher et al., 2015; Patsula et al., 2018)

The development of new methods of remediation of contaminated soils is relevant and important both in theory and practice. Phytoremediation is one of the most effective methods of decontaminating pollutants in soil using plants. It does not require soil excavation, contributes to the preservation and restoration of the environment, improves soil quality, protects it from erosion, and can be applied over large areas (Meers et al., 2007; Meers et al., 2010; de Abreu et al., 2012; Laszlo, 2014; Samokhvalova 2014; Pandey et al., 2015). Phytoremediation of soils through the cultivation of energy crops is one of the main ways to reduce the area of contaminated land and improve the state of bioenergy (Rooney et al., 2007; Witters et al., 2012; Kulyk et al., 2020; Boretska et al., 2021). The global scientific community estimates that the cost of cleaning up soil contaminated with heavy metals, radionuclides, oil, or pesticides using plants that use only solar energy is only 5% of the cost of other remediation methods. Therefore, phytoremediation is a more environmentally friendly and cheaper method of soil remediation than physical, chemical and technical methods, even taking into account the limited time resources to achieve the ultimate goal. Traditionally, phytoremediation of land is carried out to increase the productivity and sustainability of agriculture, to ensure guaranteed production of products based on the preservation and improvement of land fertility. It is also used to create the necessary conditions for the involvement of marginal lands in agricultural production and the formation of a rational structure of land (Tsytsyura et al., 2022). Phytoremediation covers a wide range of contaminants such as inorganic chemicals including heavy metals, metalloids, many organic substances including persistent organic pollutants and radioactive elements. Phytoremediation has gained great popularity over the past 20 years and is considered an acceptable technology in many countries due to its cost-effectiveness compared to traditional methods. A number of companies are engaged in phytoremediation of various contaminated sites, and several phytoremediation projects have been successfully completed around the world. The use of inedible perennial energy crops for remediation of contaminated land is considered a sustainable phytoremediation approach with economic returns (Del Grosso et al., 2014; Pandey et al., 2016). In Ukraine, there are about 3.5 million hectares of land withdrawn from crop rotation due to their low fertility, susceptibility to erosion, and contamination with heavy metals, radionuclides, and toxicants (Blum et al., 2010). Growing fast-growing, high-yielding energy crops on these lands will protect the soil from erosion, increase the capacity of the humus layer, and generally improve the country's environmental and energy situation. According to scientists, three types of energy crops are the most energy efficient: fast-growing willow (*Salix viminalis* L.), miscanthus giganteus (*Miscanthus x giganteus*), and sorghum (*Sorghum*). Highly productive plantations with a long service life are being created in Ukraine to grow them. The crops are characterized by a high rate of phytomass growth. Energy crop plantations remain productive for 20–30 years, with yields of 30–50 $Mg{\cdot}ha^{-1}$ of dry weight per year. A positive feature of energy crops is their resistance to frost, pests and pathogens. They can grow on soils of various types, wetlands and unproductive lands contaminated with heavy metals and radionuclides. In addition, these crops can adsorb large amounts of heavy metals and radionuclides from the soil, which helps clean up contaminated soils and improve their environmental condition. Countries such as Sweden, England, Ireland, Poland, and Denmark have the most experience in growing energy crops. In Ukraine, despite the large amount of land unsuitable for commercial agricultural production, industrial planting of energy crops is still insufficient (Blum et al., 2010; Rakhmetov 2011 Geletukha et al., 2014; Fedorchuk et al., 2017). Energy plants have the following impact on the ecological state and environment: one hectare of energy plantations absorbs more than 200 tons of CO_2 from the air in 3 years; ideal for planting radioactively contaminated and disturbed lands after ilmenite ore mining, low-productive or abandoned lands; effectively used in anti-erosion measures to strengthen soils, enrich them with macro- and microelements, nutrients; energy plants are natural filters for cleaning soils from pesticides; energy plantations are natural filters for removing agricultural waste, used as buffer zones in places of accumulation of biological waste from farms (Geletukha et al., 2014; Romanchuk et al., 2021). The degree of soil degradation is high, and the remediation process is complex, expensive, and slow. Soil scientists say that significant investments are needed to restore the productivity of depleted and damaged soil. The remediation of contaminated land should begin with the development of ways to use it in agricultural production, which would allow for the rapid restoration of such land and the production of safe products from it (Bellamy et al., 2009; Boehmel et al., 2008; Grabak et al., 2014;). In European countries, since 2013, there has been a common EU agricultural policy that obliges farmers who own more than 15 hectares of arable land to allocate at least 5% of the relevant area for environmental and energy needs. Such lands include, for example, clean fallow land, buffer strips, landscape elements, forest plantations, etc. Farmers are required to grow perennial energy crops on these environmentally oriented lands without the use of pesticides and mineral fertilizers. After the European Commission prepared a report on this issue in 2017, the share of land designated for environmental and energy needs should increase to 7% (Fedorchuk et al., 2017).

Currently, there are several companies in Ukraine that grow energy crops commercially. Several other companies are planning to enter this market in the near future. Rising energy prices have a negative impact on Ukraine's economy, environment, and citizens' well-being. This is the reason why Ukraine is forced to look for alternative energy sources. For this purpose, it's planned to increase the area for growing energy crops. The area for growing energy crops should be increased from 130 thousand hectares in 2020, 700 thousand hectares in 2030, and in the long run to 3.5 million hectares (Geletukha et al., 2014). For example, heavy metals and chemical pollutants, accumulating and moving through the food chain (plant-animal-human), affect various organs of animals and humans, causing diseases (Golets et al., 2009). Therefore, the systematic agricultural use of the land fund requires control over the state of its fertility, the degree of erosion, the reaction and salt regime of the soil environment, as well as the level of contamination with heavy metals, radionuclides, oil products, and pesticides. In this regard, farming on contaminated soils is one of the most pressing issues for agronomists and environmentalists. Soils contaminated with toxicants require special soil detoxification tools that could prevent them from entering crop production. Thus, the study of soil rehabilitation contaminated with organic pesticides and petroleum products for growing *Miscanthus x giganteus* and *Phalaris arundinacea* L. is quite relevant.

MATERIALS AND METHODS

The study was carried out during 2021–2023 within the CERESiS (ContaminatEd land Remediation through Energy crops for Soil improvement to liquid biofuels Strategies) H2020 Project (GA 101006717) in an experiment that was established in 2021 at the experimental field of Polissia National University, located in the Cherniakhiv district of Zhytomyr region.

To study the issue of cleaning contaminated soils from heavy metals, pesticide residues, and mineral oil products, we established trial sites of the energy plants *Miscanthus x giganteus* and *Phalaris arundinacea* L. on soils contaminated with mineral oil products (site 1) and organic pesticides (site 2) (Fig. 1). The soil of the trial sites is light loam. The depth of groundwater is approximately 2.5 m, and the upper limit of the capillary rim is 152 cm. The experiment was laid out in 3 replications, replications were arranged in one tier. The total area of the site is 540 m^2, the area of the sowing plot is 135 m^2, and the accounting plot is 100 m^2. According to the scheme of the experiment, the recommended norms of phosphorus-potassium fertilizers were applied – superphosphate (P_2O_5, 18.4%) and potassium magnesium (K_2O, 40.2%), nitrogen fertilizers – ammonium nitrate (N, 34.4%). Laboratory soil tests were carried out in accordance with existing methods and DSTU in a certified measuring laboratory of Polissia National University: certificate of conformity of the measurement system to the requirements of DSTU ISO 10012:2005 No. 0073 dated June 15, 2022. Before the experiment was set up and during the years of research, soil samples were taken from the contaminated areas: site 1 – contaminated with oil products and site 2 – contaminated with pesticides in accordance with DSTU 4287:2004, DSTU ISO 10381:2004. Standard sampling included the creation of one sample from a minimum of 25 sub-samples taken by a soil drill to the depth of the plant root system (0.1–0.9 m) with standardized soil sample preparation (fraction<2 mm, air-dried). The selected samples were analyzed in accordance with the current DSTU and methods for the following indicators: carbon content; organic matter; N; P; K; Ca; S; sum of absorbed bases; organic pollutants; phenols; gross forms of heavy metals; mobile forms of heavy metals; total forms of nutrients; oil products.

RESULTS AND DISCUSSION

Soil is a unique and irreplaceable natural resource, a solar energy storage device, the basis of life for plants, animals, and humans, and a natural indicator of environmental pollution. Before the experiment was set up in 2021, we conducted a physicochemical and agrochemical analysis of

Figure 1. Photos of *Miscanthus x giganteus* and *Phalaris arundinacea* L. at trial sites

the soil at the trial sites. The soil of the trial sites (Table 1) was characterized by a neutral reaction of the environment, a high rate of the sum of absorbed bases, very low humus and phosphorus content, very high exchangeable potassium of easily hydrolyzed nitrogen, sample No. 1 (oil-contaminated site) – very high, and sample No. 2 (pesticide-contaminated site) – high content of mobile sulfur, and increased exchangeable calcium. According to the results of the research, it was found that indicators such as the reaction of the soil solution, carbon and humus content in 2021-2023 remained almost unchanged when growing energy crops in contaminated areas (Fig. 2). However, when growing RCG, the sum of absorbed bases increased significantly – by 24.5–25.8 mmol/100 g, the content of easily hydrolyzed nitrogen by 24.3–32.3 mg·kg^{-1} and mobile phosphorus by 42–132 mg·kg^{-1} of soil. Indicators of exchangeable potassium, calcium, and mobile sulfur slightly decreased due to the removal of plants from the soil and insufficient application of mineral fertilizers (Fig. 2). When growing *Miscanthus x giganteus*, due to the large vegetative mass, the removal of macronutrients was significantly higher than their application with mineral fertilizers: the amount of absorbed bases decreased by 22.9–24.8 mmol/100 g, the content of easily hydrolyzed nitrogen by 66.3–70.1 mg·kg^{-1}, mobile phosphorus by 98.3–158.3 mg·kg^{-1}, and exchangeable potassium by 10.6 mg·kg^{-1} of soil. The content of such macronutrients as exchangeable calcium increased by 3.4–4.8 mg·kg^{-1}, and mobile sulfur by 27.1–31.0 mg·kg^{-1} (Figure 3). As noted by other researchers, miscanthus cultivation also has a positive effect on soil fertility, as it accumulates almost 20 Mg·ha^{-1} of rhizomes in the soil during four years of cultivation, which is equivalent to 7–10 Mg·ha^{-1} of organic fertilizers and significantly improves soil fertility (Blum et al., 2010; Geletukha et al., 2014; Fedorchuk et al., 2017). There are several organic and inorganic pollutants in the world, but soil contamination with heavy metals is a major concern. In the European Union, soil pollution by heavy metals accounts for more than 37% of cases, followed by 33.7% of cases of mineral oils, 13.3% of cases of polycyclic aromatic hydrocarbons, and others (Vis et al., 2010; Del Grosso et al., 2014; Pandey et al., 2016; Kulyk et al., 2020). Soil contamination with heavy metals is of global interest to modern science due to the growing man-made impact on the environment. The danger from heavy metals is determined by the fact that,

Table 1. Characteristics of the trial sites before the experiment, 2021

No.	Indicator	No. 1	No. 2	MPC	Standards
1	Exchangeable acidity, units pH (saline)	6.60	6.86	–	DSTU ISO 10390-2007
2	Exchangeable acidity, units pH (aqueous)	7.05	7,11	–	DSTU 7862:2015
3	Humus, %	1.39	1.37	–	DSTU 4289:2004
4	Carbon, %	0.81	0.79	–	DSTU 4289:2004
5	The amount of absorbed bases, mmol/100 g	23.3	22.4	–	GOST 27821-88
6	Nitrogen is lightly hydrolyzed, mg/kg of soil	89.13	97.50	–	DSTU 7863:2015
7	Mobile phosphorus, mg /kg	418.00	220.1	–	DSTU 4405: 2005
8	Exchangeable potassium, mg/kg	353.60	303.00	–	
9	Exchangeable calcium, mg/kg	11.66	14.80	–	DSTU 7945:2015
10	Sulphur, mg/kg	51.11	51.30	–	DSTU 8347:2015
Mobile compounds of chemical elements, mg/kg:					
11	Copper	0.578	0.776	3.0	DSTU 4770.6:2007
12	Zinc	10.82	15.71	23.0	DSTU 4770.2:2007
13	Lead	2.98	4.51	6.0	DSTU 4770.9:2007
14	Cadmium	0.201	0.364	0.7	DSTU 4770.3:2007
15	Nickel	1,472	1,796	4.0	DSTU 4770.7:2007
16	Chrome	6.8	12.55	6.0	DSTU 4770.8:2007
17	Manganese	17.84	19.08	140	DSTU 4770.1:2007
18	Cobalt	0.584	1.03	5.0	DSTU 4770.5:2007
Mass fraction of chemical elements, mg/kg:					
19	Copper	10,188	14,630	–	MVV 081/12-0002-01
20	Manganese	84.42	101.00	1500	MVV 081/12-0011-01
21	Zinc	42.34	50.86	–	MVV 081/12-0013-01
22	Lead	17.49	22.75	32	MVV 081/12-0009-01
23	Cobalt	5.75	7.79	–	MVV 081/12-0401-06
24	Cadmium	1.43	1.89	1.5	MVV 081/12-0010-01
25	Chrome	27.00	42.50	–	MVV 081/12-0400-06
26	Nickel	4.01	3.86	–	MVV 081/12-0003-01
27	Arsen	0.09	0.089	2.0	DSTU ISO 11464:2007
28	Vanadium	6.08	5.03	150	DSTU ISO 11464:2007
29	Stibius	172.11	161.15	4.5	DSTU ISO 11464:2007
30	Stanum	131.20	134.32	–	DSTU ISO 11464:2007
31	Mercury	0.426	0.503	2.1	MV 10.1-115-2005

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

unlike organic pollutants, they do not decompose but change from one form to another; in particular, they are included in the composition of salts, oxides, and organometallic compounds. According to forecasts, in the future, heavy metals may become more dangerous than nuclear power plant waste and share the first place with pesticides. In recent years, their environmental pollution has increased by 2.5–3 times, and 3×10^5 tons of lead and 2×10^3 tons of cadmium enter biochemical cycles annually (Romanchuk 2015; Kovalyova et al., 2020;). It should be noted that the half-life and semi-cleaning of soil from pesticides, oil products, and heavy metals take decades. Therefore, at present, the primary task of many scientists is undoubtedly to find means and measures for the phytoremediation of soils (Skachok et al., 2019). According to the research, the sites before the experiment were found to exceed the MPC for mobile forms of chromium: in the area contaminated

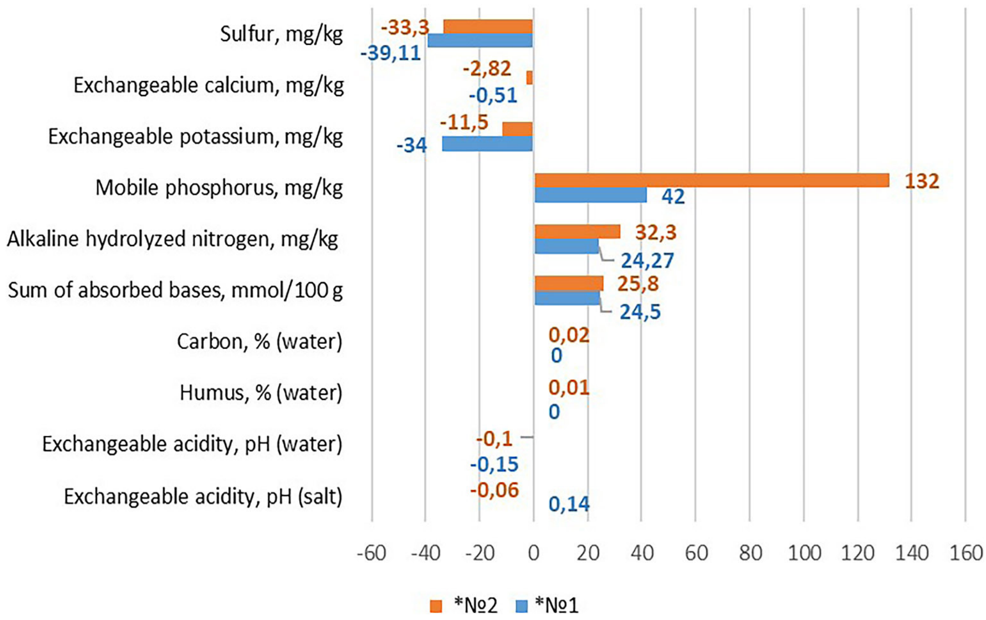

Figure 2. Changes in agrochemical and physicochemical soil parameters for energy crops, 2021–2023 on the site contaminated with oil products

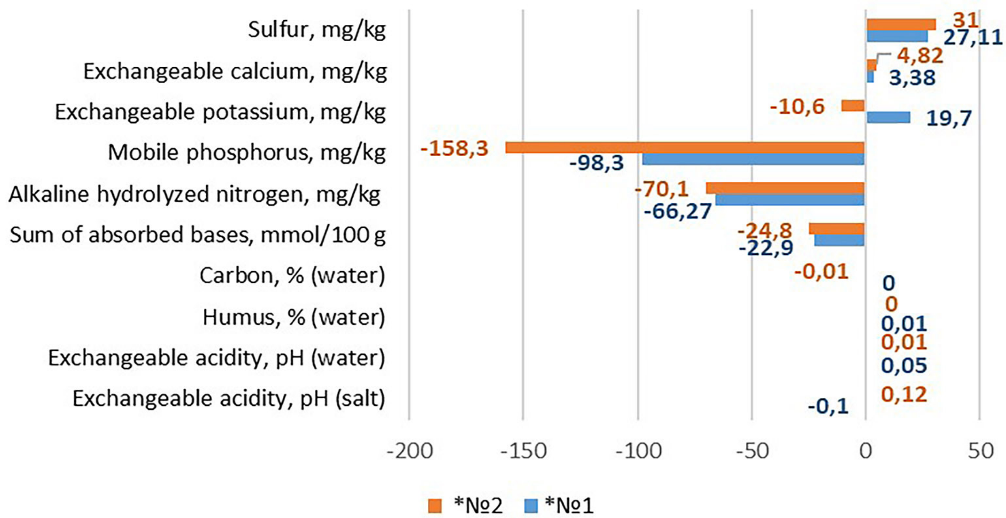

Figure 3. Changes in agrochemical and physicochemical soil parameters for energy crops, 2021–2023 on the site contaminated with pesticides

with oil products by 0.8 mg·kg^{-1}, and in the area contaminated with pesticides by 6.55 mg·kg^{-1}. The content of other heavy metal compounds was also quite high. It is known that heavy metals in soil can be found in various forms of solubility and mobility, namely: insoluble ones, which are part of soil minerals; exchangeable ones, which are in dynamic equilibrium with the ions of a given metal in the soil solution; mobile and soluble forms (Smahlii, et al., 2002). There is not only a close relationship between them, but also a possible transformation of some forms into others. Mobile forms of metals can accumulate in the soil to high concentrations that cause their toxicity to both soil biota and plants (Ryzhuk, et al., 2002) It was found that the gross antimony content was quite high and significantly exceeded the MPC: at the site contaminated with oil products it was 172.11 mg·kg^{-1} , and at the site contaminated with pesticides – 161.15 mg·kg^{-1} . A slight exceedance of the permissible level of cadmium was also detected at the site contaminated with organic pesticides – by 0.39 mg·kg^{-1}. According to the results of the research, it was found that the content of toxicants in the soil as a result of growing energy crops was significantly reduced. In particular, the content of mobile forms of heavy metals was significantly reduced when growing *Phalaris arundinacea L.*: copper – by 0.192 mg·kg^{-1} in site 1 (oil contamination) and by 0.134 mg·kg^{-1} in site 2 (pesticide contamination); zinc - by 3.83 and 4.17 mg·kg^{-1}; lead – by 0.94 and 1.05 mg·kg^{-1}; cadmium – by 0.041 and 0.057 mg·kg^{-1}; nickel –by 0.092 and 0.274 mg·kg^{-1}; chromium – by 0.55 and 3.65 mg·kg^{-1}; manganese – by 5.33 and 3.15 mg·kg^{-1}; cobalt – by 0.301 and 0.201 mg·kg^{-1}, respectively (Fig. 4). Our studies have shown that, compared to *Palaris arundinacea L.*, *Miscanthus × giganteus*, due to its larger biomass, removed significantly more heavy metals from the soil, except for zinc. The content of copper was 0.208 mg·kg^{-1} in site 1 (contaminated with oil products) and site 2 (contaminated with pesticides); zinc –by 1.94 and 3.31 mg·kg^{-1} ; lead – by 1.94 and 2.06 mg·kg^{-1}; cadmium – by 0.097 and 0.108 mg·kg^{-1}; nickel – by 0.152 and 0.382 mg·kg^{-1}; chromium – by 1.06 and 5.25 mg·kg^{-1}; manganese – by 7.43 and 3.92 mg·kg^{-1}; cobalt – by 0.338 and 0.408 mg·kg^{-1}, respectively (Fig. 5). The gross content of heavy metals was also significantly reduced when growing energy crops on contaminated soils.. Copper concentration decreased in the sites where energy crops were grown: for *Phalaris arundinacea* L. by 17%, for *Miscanthus giganteus* by 33–20%; manganese by 10–16% and 13–32%; zinc by 16–12% and 18–10%; lead by 62–59% and 73–67%; cobalt by 35–24% and 65–59%; cadmium – by 9–10% and 13–17%; chromium – by 11–7% and 15–6%; nickel – by 3% and 17–4%; arsenic – by 20–16% and 10–12%; vanadium – by 5–2%

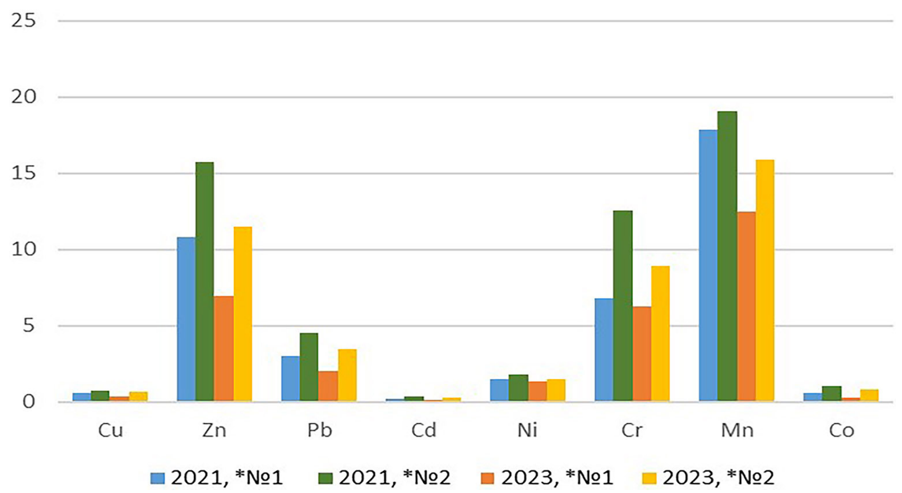

Figure 4. Changes in the content of mobile compounds of chemical elements during 2021–2023 for the cultivation of *Phalaris arundinacea* L., mg·kg^{-1}

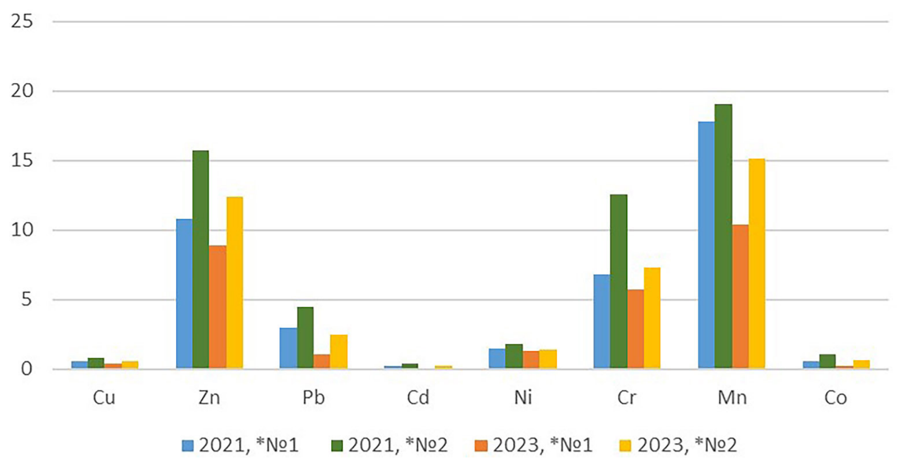

Figure 5. Changes in the content of mobile compounds of chemical elements during 2021–2023 for the cultivation of *Miscanthus x giganteus*, mg·kg^{-1}

Note: No. 1 – the site is contaminated with oil products; No. 2 – the site is contaminated with pesticides and 7–4%; antimony (stibium) - by 35–20% and 40–39%; stanum - by 15–29% and 20–38%; mercury - by 38–49% and 47–54%, respectively (Fig. 6,7).Other scientists confirm the decrease in the content of heavy metals in soils when growing energy crops, namely mobile compounds of lead, cadmium, copper and zinc (Kovalyova et al., 2020). Along with the ability of energy crops to phytoremediation of heavy metal-contaminated soils, it has been established that they have the potential to decompose organic pollutants, in particular, polycyclic aromatic hydrocarbons. Crop root exudates have been shown to have a destructive capacity, decomposing pyrene and phenanthrene (Wanat et al., 2013; Gawronski et al., 2017). Polyphenolic compounds, flavonoids present in the rhizosphere, such as *M. giganteus*, have been found to stimulate the growth of microorganisms that utilize polycyclic aromatic hydrocarbons (Wanat et al., 2013; Barbosa et al., 2015).

When determining organic pollutants in the soil, DDT and its metabolites were not detected in the trial sites (Table 2). Heptachlor was detected on a pesticide-contaminated site; as a result of growing energy crops, its content in the soil decreased by 0.001 mg·kg^{-1} after *Phalaris arundinacea* L. and by 0.002 mg·kg^{-1} after *Miscanthus x giganteus* during 2021–2023.

The total of Hexachlorocyclohexane (HCH), sum of isomers at site 1 contaminated with oil products was 0.245 mg·kg^{-1}, at site 2 contaminated with pesticides – 0.28 mg·kg^{-1}, which exceeded the MPC by more than 2 times. In site 1, its content decreased by 0.099 mg·kg^{-1}, when growing RCG, by 0.121 mg·kg^{-1}, when growing miscanthus, and by 0.12 and 0.143 mg·kg^{-1} , respectively, in site 2.

The content of 2,4-D-amine salt in the soil did not change during the cultivation of energy crops and was at the level of 0.05 mg·kg^{-1} in 2021. The content of petroleum products in site 1, which was contaminated with petroleum products before the experiment, exceeded the permissible level by more than 4 times, and in site 2 contaminated with pesticides - by 191 mg·kg^{-1}. When growing RCG, their content decreased in the area contaminated with petroleum products by 1364.14 mg·kg^{-1}; in the area contaminated with pesticides by 565.52 mg·kg^{-1}. Growing Miscanthus giganteus also significantly reduced their content in the soil –by 1160.08–564.15 mg·kg^{-1}, respectively. The content of phenols in the area contaminated with oil products was 0.5 mg·kg^{-1} and was halved by growing energy crops, while their content was not detected in the area contaminated with pesticides.

CONCLUSIONS

Growing energy crops as phytoremediation on contaminated lands will not only reduce the level of degradation but also increase the agronomic value of these soils. The high biomass

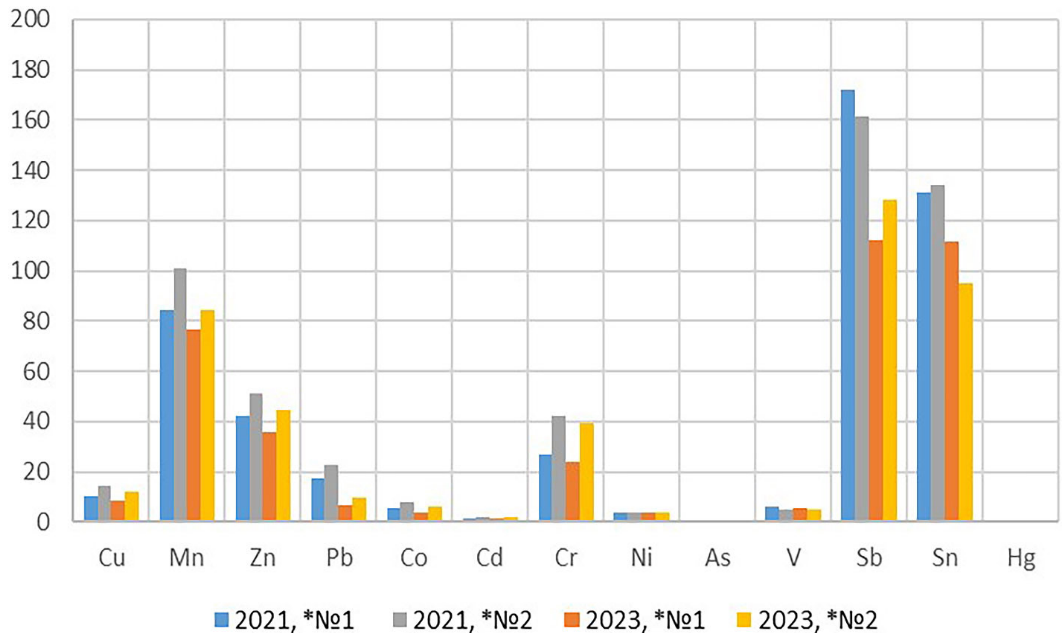

Figure 6. Changes in the mass fraction of chemical elements during 2021–2023 for the cultivation of *Phalaris arundinacea* L., mg·kg^{-1}

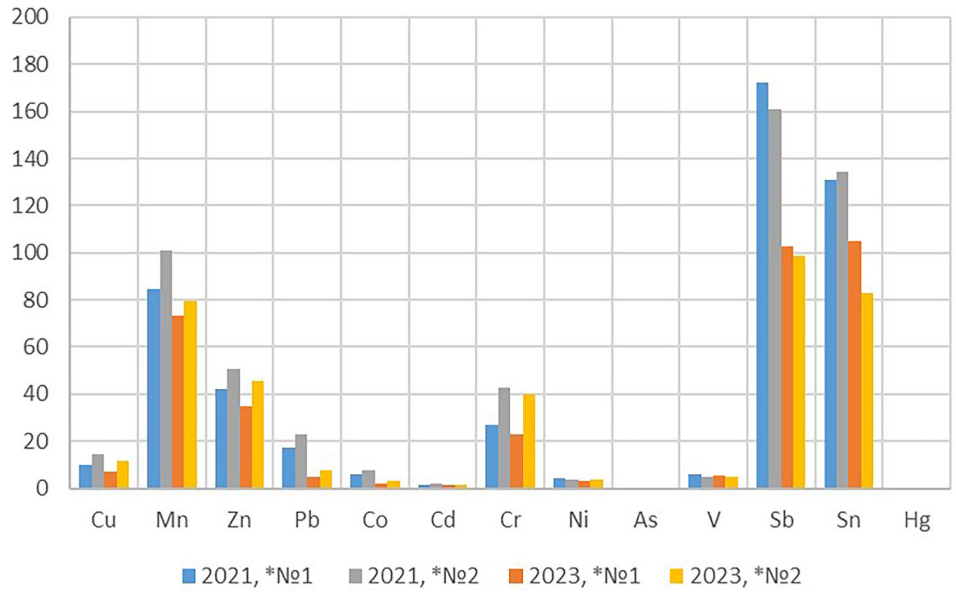

Figure 7 Changes in the mass fraction of chemical elements during 2021–2023 for the cultivation of *Miscanthus x giganteus*, mg·kg^{-1}

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

Table 2. Content of organic pollutants before and after growing energy crops, mg·kg^{-1}

Organic pollutants, mg/kg	Before the start of the experiment, 2021		*Phalaris arundinacea*				*Miscanthus x giganteus*				MPC
			2023		+/-, mg/kg		2023		+/-, mg/kg		
	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	No. 1	No. 2	
DDT and its metabolites	nd	nd	nd	nd	–	–	nd	nd	–	–	0.1
Heptachlor	nd	0.03	nd	0.029	–	0.001	nd	0.028	–	0.002	0.05
HCH (sum of isomers)	0.245	0.28	0.146	0.16	0.099	0.12	0.124	0.137	0.121	0.143	0.1
2,4- D-amine salt	0.05	0.05	0.05	0.05	–	–	0.05	0.05	–	–	0.25
Oil products	2089	691	724.8	125.4	1364.1	565.5	928.9	126.8	1160.1	564.1	500
Phenols	nd	0.5	nd	0.25	–	0.25	nd	0.27	–	0.23	4

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

productivity of energy crops can turn phytoremediation technology into a profitable industry for the bioenergy industry. Energy crops accumulate organic matter in the soil, increasing its carbon content, intensively absorb carbon dioxide and reduce the effects of global warming. According to the results of the research, it was found that the reaction of the soil solution, carbon and humus content remained almost unchanged during 2021–2023 when growing energy crops in areas contaminated with oil products and pesticides. When growing *Phalaris arundinacea* L. on contaminated soils, the sum of absorbed bases, the content of easily hydrolyzed nitrogen, and mobile phosphorus increased significantly, while the content of exchangeable potassium, calcium, and mobile sulfur decreased slightly. In the trial sites, when growing *Miscanthus x giganteus*, the content of macronutrients slightly decreased due to the large vegetative mass and insufficient application of mineral fertilizers, while the content of exchangeable calcium and mobile sulfur slightly increased. The content of mobile forms of heavy metals in the soil as a result of growing energy crops decreased significantly. In particular, the content of chromium decreased: in the area contaminated with pesticides by 0.55 mg·kg^{-1} (8.09%), when growing RCG and by 1.06 mg·kg^{-1} (15.59%) when growing miscanthus, and in the area contaminated with oil products by 3.65 (29.08%) and 5.25 mg·kg^{-1} (41.83%), respectively. The content of the mass fraction of heavy metals, especially antimony, also significantly decreased: on the site contaminated with pesticides – by 60 mg·kg^{-1} (38.8%) when growing RCG and by 69.61 mg·kg^{-1} (20.48%) of soil when growing miscanthus, on the site contaminated with oil products – by 65.68 (40.45%) and 78.35 mg·kg^{-1} (34.86%). The concentration of cadmium in the studied sites where energy plants were grown decreased in the range of 0.131–0.193 mg·kg^{-1} (29.67–48.26%) when growing *Phalaris arundinacea* L. *and* by 0.187–0.312 mg·kg^{-1} (15.66–20.4%) when growing *Miscanthus x giganteus*, respectively. The content of HCH (sum of isomers) – in the area contaminated with pesticides decreased by 0.099 mg·kg^{-1} (4,041%) when growing RCG, by 0.121 mg·kg^{-1} (42,8%) when growing miscanthus, in the area contaminated with oil products – by 0.12 (2.42%) and 0.143 mg·kg^{-1} (4.38%), respectively. As for the presence of petroleum products, the best result was observed in the trials where *Phalaris arundinacea* L. was grown - their content decreased by 1364.14 mg·kg^{-1} (34.7%) on the site contaminated with oil products and by 565.52 mg·kg^{-1} (18.2%) on the site contaminated with pesticides. Growing *Miscanthus x giganteus* also significantly reduced their content in the soil – by 1160.08 (24.88%) – 564.15 mg·kg^{-1} (34.74%), respectively. The content of phenols in the area contaminated with oil products was 0.5 mg·kg^{-1} and was halved by growing energy crops.

The results of the study of soil remediation contaminated with organic pesticides and fuel oil under the cultivation of *Miscanthus x giganteus* and *Phalaris arundinacea* L. plants showed that they are able to accumulate both heavy metals and organic pollutants and oil products.

REFERENCES

1. Blum Y.B., Geletukha H.G., Grygoryuk I.P. 2010. The latest technologies of bioenergy conversion. Kyiv: Agrar Media Group. [in Ukrainian]
2. Boretska I.Y., Dzura N.M., Romaniuk O.I. 2021. Phytoremediation of technologically polluted soils using energy crops. Environmental sciences. 6(39). 72–76. doi: 10.32846/2306-9716/2021.eco.6-39.11[in Ukrainian]
3. Geletukha H.G., Zhelezna T.A. 2014. Prospects for using agricultural waste for energy production in Ukraine. Analytical note of BAU.7. 12–16. [in Ukrainian]
4. Hrabak N.H., Budykina Y.I. 2014. Technogenically polluted lands and ways of their safe use in the agro-industrial complex. Scientific works. Ecology. 220 (232). 83–87. [in Ukrainian]
5. Tsytsiura Y.G., Shkatula Y.M., Zabarna T.A., Peleh L.V. 2022. Innovative approaches to phytoremediation and phytoremediation in modern farming systems. Vinnytsia: “Druk” LLC. 1200 p. [in Ukrainian]
6. Kulyk M.I., Galytska M.A., Samoylik M.S., Zhornyk I.I. 2019. Phytoremediation aspects of energy crops use in Ukraine. Agrology, 2(1), 65–73. doi: 10.32819/2617-6106.2018.14020 [in Ukrainian]
7. Ilyashenko N.S. 2020. Management of strategies of anticipatory innovative development. Sumy: Tritoria, pp. 109–118. [in Ukrainian]
8. Laszlo O.O. 2014. Restoration of disturbed agricultural land with the help of bioremediation. Bulletin of the National University of Water Management and Nature Management. 1 (65). 94–100. [in Ukrainian]
9. Patsula O.I. Fetsyukh A.B. Bunyo L.V. 2018. Use of *Salix viminalis* L. for phytoremediation of soils contaminated with heavy metals. Environmental sciences. 2(20). 101–106. [in Ukrainian]
10. Rakhmetov D.B. 2011. Theoretical and applied aspects of plant introduction in Ukraine. Kyiv: Agrar Media Group. 398 p. [in Ukrainian]
11. Romanchuk L.D., Kovalev V.B., Mozharivska I.A. 2021. Cultivation of giant miscanthus in conditions of radioactive contamination. Collection of works of the participants of the International Scientific and Practical Conference “Chernobyl Catastrophe. Actual problems, directions and ways to solve them” (April 22–23, 2021). Zhytomyr: University of Polissia. P. 68–73. [in Ukrainian]
12. Samokhvalova V.L. 2014. Biological methods of remediation of soils contaminated with heavy metals. Biological studies. 8(1). 217–236. [in Ukrainian]
13. Skachok L.M., Potapenko L.V., Gorbachenko N.I. 2019. Agroecological efficiency of elements of miscanthus growing technology on radioactively contaminated soils. Visnyk Agrar. Science 9. 59–66. [in Ukrainian]
14. Fedorchuk M.I., Kokovikhin S.V., Kalenska S.M. 2017. Agrotechnological aspects of growing energy crops in southern Ukraine. Kherson. 42–45. [in Ukrainian]
15. Barbosa B., Boléo S., Sidella S., Costa J., Duarte M.P., Mendes B., Cosentino S.L., Fernando A.L. 2015. Phytoremediation of heavy metal-contaminated soils using the perennial energy crops *Miscanthus* spp. and *Arundo donax* L. Bioenergy Research, 8(4), 1500–1511. doi: 10.1007/s12155-015-9688-9
16. Basumatary B., Saikia R., Bordoloi S. 2012. Phytoremediation of crude oil-contaminated soil using nut grass Cyperus rotundus. Journal of Environmental Biology, 33(5), 891–896.
17. Bellamy P.E., Croxton P.J., Heard M.S., Hinsley S.A., Hulmes L., Nuttall P., Pywell R.F., Rothery P. 2009. The impact of growing miscanthus for

biomass on farmland bird populations. Biomass and Bioenergy, 33(2), 191–199. doi: 10.1016/j.biombioe.2008.07.001

18. Boehmel C., Lewandowski I., Claupein W. 2008. Comparing annual and perennial energy cropping systems with different management intensities. Agricultural Systems, 96(1–3), 224–236. doi: 10.1016/j.agsy.2007.08.004
19. de Abreu C.A., Coscione A.R., Pires A.M., Paz-Ferreiro J. 2012. Phytoremediation of a soil contaminated by heavy metals and boron using castor oil plants and organic matter amendments. Journal of Geochemical Exploration, 123, 3–7. doi: 10.1016/j.gexplo.2012.04.013
20. Gawronski S.W., Gawronska H., Lomnicki S., Sæbo A. 2017. Plants in Air Phytoremediation. Advances in Botanical Research, 83, 319–346. doi: 10.1016/bs.abr.2016.12.008
21. Golets N.Y., Mal′ovanyy M.S., Malyk Y.O. 2009. Investigation of the properties of the filtration screen of solid waste landfill. Bulletin of the National University "Lviv Polytechnic", 644, 195–198.
22. Kovalyova S., Mozharivska I. 2020. Heavy metal concentration in soils while growing energy crops in the radioactively contaminated territory. Scientific Horizons, 03(88), 121–126. doi: 10.33249/2663-2144-2020-88-3-121-126
23. Meers E., van Slycken S., Adriaensen, K., Ruttens A., Vangronsveld J., Laing G.D., Witters N., Thewys T., Tack F.M.G. 2010. The use of bio-energy crops (Zea mays) for 'phytoattenuation' of heavy metals on moderately contaminated soils: a field experiment. Chemosphere, 78(1), 35–41. doi: 10.1016/j.chemosphere.2009.08.015
24. Meers E., Vandecasteele B., Ruttens A., Vangronsveld J., Tack F. M.G. 2007. Potential of five willow species (*Salix* spp.) for phytoextraction of heavy metals. Environmental and Experimental Botany, 60(1), 57–68. doi: 10.1016/j.envexpbot.2006.06.008
25. Moubasher H.A., Hegazy A.K., Mohamed N.H., Moustafa Y.M., Kabiel H., Hamad A.A. 2015. Phytoremediation of soils polluted with crude petroleum oil using Bassia scoparia and its associated rhizosphere microorganisms. International Biodeterioration and Biodegradation. 98, 113–120. doi: 10.1016/j.ibiod.2014.11.019
26. Pandey V.C., Bajpai O., Singh N. 2016. Energy crops in sustainable phytoremediation. Renewable and Sustainable Energy Reviews, 54, 58–73. doi: 10.1016/j.rser.2015.09.078
27. Pandey V.C., Pandey D.N., Singh N. 2015. Sustainable phytoremediation based on naturally colonizing and economically valuable plants. Journal of Cleaner Production, 86, 37–39. doi: 10.1016/j.jclepro.2014.08.030
28. Ridej N.M., Tonxa O.L., Shofolov D.L. 2009. Land protection and sustainable land use. Lugans`k: TOV PROGTEXSNAB.
29. Romanchuk L.D. 2015. Radioekolohichna otsinka formuvannia dozovoho navantazhennia u meshkantsiv silskykh terytorii Polissia Ukrainy. Zhytomyr: Polissia.
30. Rooney W.L., Blumenthal J., Bean B., Mullet J. 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels, Bioproducts, Biorefining. 1, 147–157. doi:10.1002/bbb.15
31. Ryzhuk S.M., Sliusar I.T., Verhunov V.A. 2002. Agroecological features of highly effective use of drained peat soils in Polissia and Forest-Steppe. Kyiv: Agrarna Nauka.
32. Smahlii O.F., Rybak M.F., Dankevych Y.M. 2008. Basics of agriculture. Zhytomyr: Publishing house of VDNZ "Derzh. agroecol. univ.
33. Stephen D.G., Pete S., Marcelo G., Astley H., William P. 2014. Sustainable energy crop production. Current Opinion in Environmental Sustainability. 9–10, 20–25. doi: 10.1016/j.cosust.2014.07.007
34. Vis M.W., van den Berg D. 2010. Biomass Energy Europe Harmonization of biomass resource assessments. Vol. I. Best Practices and Methods Handbook. Italy.
35. Wanat N., Austruy, A., Joussein, E., Soubrand, M., Hitmi, A., Gauthier-Moussard, C., Lenain, J.F., Vernay P., Munch J.C., Pichon M. 2013. Potentials of *Miscanthus × giganteus* grown on highly contaminated Technosols. Journal of Geochemical Exploration, 126–127, 78–84. doi: 10.1016/j.gexplo.2013.01.001
36. Witters N., Mendelsohn R.O., Van Slycken S., Weyens N., Schreurs E., Meers E., Tack F., Carleer R., Vangronsveld J. 2012. Phytoremediation, a sustainable remediation technology? Conclusions from a case study. In: Energy production and carbon dioxide abatement. Biomass and Bioenergy, 39, 454–469. doi: 10.1016/j.biombioe.2011.08.016