JEE

Journal of Ecological Engineering

ISSN 2299-8993

OPEN ACCESS

Editorial Board

All issues

Volume 25, Issue 9, 2024

IN PROGRESS

JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(9), 282–291
https://doi.org/10.12911/22998993/191439
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.07.05
Accepted: 2024.07.22
Published: 2024.08.01

Accumulation of Chemical Elements in the Vegetative Mass of Energy Cultures Grown on Gray Forest Soils in the Western Forest Steppe of Ukraine

Serhii Razanov[1*], Oleksii Alieksieiev[1], Oleh Bakhmat[2], Mykola Bakhmat[2], Olha Lytvyn[3], Olha Alieksieieva[1], Oksana Vradii[1], Kateryna Mazur[1], Alla Razanova[1], Iryna Mazurak[3]

[1] Vinnytsia National Agrarian University, Soniachna Str. 3, Vinnytsia, 21008, Ukraine
[2] Higher Education Institution Podillia State University, Shevchenko Str. 12, Kamianets-Podilskyi, 32316, Ukraine
[3] Lviv National Environmental University, Volodymyra Velykoho Str. 1, Dublyany, Lviv Region, 30831, Ukraine
* Corresponding author's e-mail: razanovsergej65@gmail.com

ABSTRACT

Today, energy crops that are undemanding to soil fertility are increasingly used for the production of biofuel, electricity, and heat. Favorable climate, large areas of agricultural lands of Ukraine create the necessary conditions for growing the most popular energy crops, which will be able to supply the domestic market, as well as export. The article is aimed at studying the accumulation of chemical elements phosphorus (P), potassium (K), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb) in the vegetative mass of *Miscanthus*, *Silphium perfoliatum L.* and *Sida hermaphrodita L. Rusby* for their cultivation in the conditions of the Western Forest Steppe of Ukraine on gray forest soils. The article presents the results of own field and laboratory research.

Keywords: heavy metals, gray forest soil, vegetative mass, *Miscanthus*, *Silphium perfoliatum L., Sida hermaphrodita L. Rusby*.

INTRODUCTION

A special characteristic of perennial energy crops is that they have a high level of productivity, are undemanding to soil fertility and high levels of mechanization of production processes. During a fairly short period of vegetation, energy plants are capable of a significant increase in biomass (Didenko et al., 2023). From an economic point of view, if you recalculate the received energy, the costs of growing energy crops are significantly lower than the cost of energy carriers that are obtained in the traditional way. The use of plant biomass of these crops, provided it is continuously regenerated, does not lead to an increase in the concentration of CO_2 in the atmosphere, which is ecologically appropriate (Kaletnik et al., 2020).

Practice shows that the use of energy crops as a source of energy is growing rapidly in European countries. Since the beginning of 2000, there has been a certain interest in the cultivation of energy crops in Ukraine (Branitsky et al., 2019).

Among the most common energy crops grown on the territory of Ukraine are: *Miscanthus* and energy willow (*Salix*) to a lesser extent *Silphium perfoliatum L.* and *Sida hermaphrodita L. Rusby*, which have been growing on energy plantations for about 20 years. Along with these crops, the following are of scientific interest: cane arundo (*Arundo donax*) (Branitsky et al., 2022), sugar sorghum (*Sorghum bicolor*), and perennial sorghum (*Sorghum almum Parodi*) (Gumentyk et al., 2020).

Miscanthus-belongs to the family of cereals (*Gramineae*), a perennial grassy crop with a well-developed root system that reaches more than 2.5 m deep into the soil. Due to such a root system, the plant quite powerfully uses nutrients and moisture from the lower soil horizons (Lopushniak et al., 2022). *Miscanthus* has fairly strong stems and is highly resistant to mechanical damage, as it contains a significant amount of lignin and cellulose in its composition (Honcharuk et al., 2020). *Miscanthus* plants overwinter quite well and are resistant to precipitation and wind. *Miscanthus* is very demanding on water than the average annual precipitation available to it – about 600–700 mm per year. But, even under these conditions, water consumption for the production of 1 kg of dry mass is quite low. Soils for planting *Miscanthus* should have neutral acidity (pH = 6.5), especially during the first two years of growth, and the groundwater level should not be below 1 m. biomass can be harvested annually (Kaletnik et al., 2020). *Miscanthus* is a valuable raw material for the production of high-quality fuel pellets due to its high content of cellulose and lignin. Production costs for growing *Miscanthus* biomass in various European countries are at the level of 40–50 euros/t of dry matter (Kaletnik et al., 2014).

Silphium perfoliatum L. is a culture of various economic uses. It is grown for green fodder, for the production of silage and grass flour.The green mass of *Silphium perfoliatum L.* has a low fiber content and a large amount of vitamins, and therefore it is a valuable raw material for the preparation of vitamin herbal flour, which is not inferior in quality to flour from legumes (Kaletnik et al., 2019). Grass meal is a valuable feed for all types of animals, especially for poultry. In young plants, leaves make up to 70% of the green mass – the most valuable and nutritious part of the crop, although, unlike many tall plants, the juicy stems of *Silphium perfoliatum L.* also have relatively good nutritional properties (Kaletnik et al., 2021).

High-quality grass flour can be made from the green mass of *Silphium perfoliatum L.*, due to its low fiber content and high carotene content. *Silphium perfoliatum L.* plants are large-stemmed and have a high moisture content of more than 85%, due to which, during mowing, they require a mandatory application of the mass for the production of vitamin flour (Kharytonov et al., 2023). This measure reduces fuel consumption by 10–15% and increases the productivity of units. Due to the high sugar content (14–20%), the normal ensiling process of green mass is determined (Kharytonov et al., 2021).

As for fodder qualities, it should be noted that the productive potential of *Silphium perfoliatum L.* is very high. From one hectare, the crop yields an average of 100 tons or more of green mass within 15–25 years (Kharytonov et al., 2024). Also, *Silphium perfoliatum L.* plays an important role in the protection of the natural environment. Due to the well-developed root system, the plant contributes to the consolidation of the upper layer of the soil and is an effective means of combating soil erosion, loss of mineral elements from surface runoff and their infiltration into deep layers (Palamarchuk et al., 2019). *Silphium perfoliatum L.* increases the content of humus and water-resistant aggregates in the soil, which improves the use of soils under irrigation conditions (Kharytonov et al., 2023).

The culture blooms intensively in the second half of summer for four to five decades, attracting a large number of bees. The remanent type of flowering makes it possible to use the culture as a good honey plant. Unlike most other plants, sylphium flowers intensively secrete nectar during the entire light period of the day. With a solid grass stand, the productivity of honey collection reaches 150 kg/ha (Mykolenko et al., 2022).

Sida hermaphrodita L. Rusby is a species of Seed belonging to the mallow family, which includes several hundred species of annual plants, perennials and shrubs growing in tropical and subtropical zones of the globe (Kharytonov et al., 2019).

It grows poorly on overmoistened, flooded soils and does not tolerate flooding. *Sida hermaphrodita L. Rusby* is a frost-resistant and drought-resistant culture. Forms a powerful root system, grows even on slopes. A perennial plant can grow in one place for 15–20 years (Kharytonov et al., 2019).

The plants grow in height from 1.20 to 2.10 meters. Biomass harvesting is carried out annually, the yield is from 12 to 25 t/ha of dry mass (depending on growing conditions) (Zulauf et al., 2018). The collected biomass is characterized by low ash content (2–3%) and low moisture content (19.3%), which is very important, since the cost of biomass drying is reduced during processing into fuel pellets. The biomass of this crop is a promising source of renewable energy. In terms of heat generation when burning mallow stems, only beech wood is inferior (by 20–34%) (Kharytonov et al., 2019).

The results of laboratory studies of the green mass of energy crops *(Silhium perfoliatum L.*, *Sorghum almum Parodi*, *Bunias orientalis L.*, *Sida hermaphrodita Rusby*, *Miscanthus giganteus G.*) showed that all studied crops did not exceed the established standard for the content of heavy metals for feed (Kharytonov et al., 2019). That is, it was found that in the conditions of man-made stress on soils, in particular their contamination with heavy metals, energy crops can accumulate these toxicants in their biomass (Pryshliak et al., 2020). It is generally known that, the accumulation and absorption of heavy metals by plants, including energy ones, is determined by a large number of factors: the type of soil, its physical and physicochemical properties, the content of organic matter, oxidation-reduction reactions, temperature conditions of the soil, vegetation characteristics, etc. (Kulyk et al., 2020).

Entering from the soil into plants through the root system, heavy metals can move actively or passively. In the first case, the absorption and movement of metal ions is carried out by a system consisting of protoplasts of cells connected by plasmodesmata (Dydiv et al., 2023). With passive transport, ions, having reached the surface of the root, enter the free space of the root and move further along the plant with the transpiration current. With active transport, a part of metals that perform some biological functions (copper, zinc, cobalt, etc.), as well as metals that are chemically similar to the necessary elements (cadmium is a chemical analog of zinc) moves through the plant (Dovhalyuk, 2013).

Comparing the concentration of lead in the phytomass of plants, it should be noted that the highest content of this element was noted in the plants of *Silphium perfoliatum L.* and scurbiga orientalis (Kuraeva et al., 2012). This indicator was in the range of 2.65–2.89 and 2.53–2.77 mg/kg, respectively, by culture. The difference in lead content between the fertilizer options was also noted, i.e. the lowest concentration of this element was for the cultivation of all energy crops in the option without fertilizers – 1.65–2.65 mg/kg. For the cultivation of perennial sedum, miscanthus giganteus, perennial sorghum, oriental itch, and prickly-leaved *Silphium perfoliatum L.*. With the use of mineral fertilizers, the content of lead in the phytomass of the studied plants compared to the control was higher by 7.3; 8.0; 8.4; 9.0; 9.5% (Razanov et al., 2023). The concentration of cadmium in plants of energy crops varied from 0.186 to 253 mg/kg. The lowest concentration of cadmium was noted in the phytomass of perennial sedum (0.186–0.198 mg/kg), and the highest in plants of *Silphium perfoliatum L.* (0.234–0.253 mg/kg) (Razanov et al., 2024). When growing energy crops in variants without fertilizers, the cadmium content was 6.9–8.6% higher compared to the control. As for toxicants such as copper and zinc, their content in the phytomass of energy crops grown on radioactively contaminated territories was also significantly below the MPC and was in the range of 4.00–5.79 and 25.55–34.50 mg/kg, in accordance (Razanov et al., 2023). The concentration of copper was the highest in the plants of scurvy orientalis (5.26–5.47 mg/kg) and *Silphium perfoliatum L.* (5.60–5.79 mg/kg). The lowest gross content was noted in perennial sedum plants, where the concentration of the toxicant was in the range of 4.00–4.21 mg/kg. The highest zinc content was noted in plants of *Silphium perfoliatum L.*, where its concentration varied from 32.83 to 34.50 mg/kg (Kozlovsky et al., 2005). The lowest concentration of zinc was found in plants of *Miscanthus giganteus* and perennial seed grown without the use of fertilizers (25.55–26.44 mg/kg). It was also established that during the cultivation of energy crops in variants with the use of mineral fertilizers, an insignificantly increased content of copper and zinc in phytomass was observed compared to the cultivation of crops without fertilizers (Razanov et al., 2022). In particular, the copper content was higher by 3.3; 3.8; 4.3; 4.6; 5.0% for the cultivation of *Silphium perfoliatum L.*, scurvy orientalis, perennial sorghum, *Miscanthus giganteus* and perennial sedum, and the zinc content is higher by 5.1; 5.7; 6.0; 6.3; 6.7%, respectively (Holovach et al., 2004).

The cultivation of energy crops is accompanied by the removal of various chemical substances from the soil with the vegetative mass of plants, which leads to a change in their agrochemical composition. Along with this, the use of vegetative mass of energy crops as a raw material for biofuel can lead to the introduction of harmful substances into the environment, in particular, heavy metals.

Under such conditions, there is a need to monitor the level of accumulation of chemicals in the vegetative mass of energy crops in order to predict the release of toxicants into the environment due to its use as biofuel and to restore the agrochemical composition of the soils on which these crops have been grown when they are transferred to a field crop rotation for the cultivation of agricultural crops.

In this regard, the aim of the research was to study the intensity of accumulation of chemical elements (P, K, Cu, Zn, Cd and Pb) in the vegetative mass of *Miscanthus*, *Silphium perfoliatum L.* and *Sida hermaphrodita L. Rusby* when grown under field crop rotation on grey forest soils of the Western Forest-steppe of Ukraine.

MATERIALS AND METHODS

The study of the accumulation of chemical elements in the vegetative mass of energy crops was carried out in the conditions of the western Forest-Steppe of Ukraine. The research scheme included three options, the first of which was aimed at growing and determining the content and accumulation rate of chemicals in the vegetative mass of *Miscanthus*. The second option determined the content and accumulation rate of chemicals in the vegetative mass of *Silphium perfoliatum L.*, while the third one in the vegetative mass of *Sida hermaphrodita L. Rusby*. Each option included four repetitions.

The selection of soil from each section of the area was carried out by the envelope method, the essence of which consists in the selection of soil at five points of each area at the depth of its plowing and the formation of an average sample of 0.5 kg.

Vegetative mass of energy crops (*Miscanthus*, *Silphium perfoliatum L., Sida hermaphrodita L. Rusby*), grown on gray forest soils, was selected for research by the point method, 3.0 kg from each crop. Vegetative mass included stem and leaves. The accumulation coefficient was determined by the formula:

$$H\ rat. = \frac{\text{ACP}}{\text{MPC}} \quad (1)$$

where: *H rat.*– pollutant hazard ratio, *ACP* – actual pollutant concentration in the in vegetative mass, mg/kg; *MPC* – maximum permissible concentration of heavy metals and trace elements, mg/kg.

The content of chemical substances, in particular mobile forms of P and K were determined according to USS 4115:2002, Cu – according to DSTU 4770.6:2007, Zn – according to DSTU 4770.2:2007, Cd – according to DSTU 4770.3:2007 and Pb – according to DSTU 4770.9:2007 (DSTU 2009).

Biometric processing of the obtained research results was carried out taking into account the arithmetic mean value (M), the mean square deviation (m) and the reliability of the difference between the mean values (criteria P). Conventional symbols are used to show the probability in the tables: $P < 0.05^{*}$; $P < 0.01^{**}$; $P < 0.001^{***}$.

RESULTS AND DISCUSSION

According to the research results (Table 1), the highest content of zinc in the vegetative mass of *Miscanthus* was found, which was 9.1 mg/kg. In particular, the content of zinc in the vegetative mass of *Miscanthus* was higher compared to phosphorus by 111 times, potassium by 22.2 times and copper by 2.8 times.

Among the heavy metals, lead was detected 1.2 times more in the vegetative mass of *Miscanthus* compared to cadmium. The sequence of the content of chemical elements in the vegetative mass of *Miscanthus* was increasing in the following correspondence: cadmium – lead – phosphorus – potassium – copper–- zinc.

Analyzing the coefficient of accumulation of chemical elements in the vegetative mass of *Miscanthus* (Table 2), it should be noted that the highest indicator was observed for copper, which was 16.7. In particular, in the vegetative mass of *Miscanthus*, a higher coefficient of copper accumulation was observed compared to phosphorus by 27833 times, potassium by 4513 times and zinc by 1.3 times. The sequence of the coefficient of accumulation of chemical elements in the vegetative mass of *Miscanthus* grew in the following order: phosphorus – potassium – cadmium – lead – zinc – copper. Thus, among heavy metals, the accumulation rate of lead was 1.25 times higher than that of cadmium.

Table 1. Content of chemical elements in the vegetative mass of *Miscanthus*, (n = 4, M ± m)

Indicators	Unit of measurement	Content of substances in the vegetative mass				On average for the options
		I	II	III	IV	
Phosphorus (P)	mg/kg	0.080	0.078	0.083	0.086	0.082 ± 0.004
Potassium (K)	mg/kg	0.40	0.40	0.42	0.42	0.41 ± 0.01
Copper (Cu)	mg/kg	3.2	3.3	3.1	3.2	3.2 ± 0.5
Zinc (Zn)	mg/kg	9.2	9.3	9.0	8.9	9.1 ± 0.2
Cadmium (Cd)	mg/kg	0.00012	0.0001	0.00009	0.00009	0.0001 ± 0.00004
Lead (Pb)	mg/kg	0.0010	0.0013	0.0011	0.0014	0.0012 ± 0.0003

Table 2. The coefficient of accumulation of chemical elements in the vegetative mass of *Miscanthus*

Indicators	Unit of measurement	Actual concentration		Accumulation factor
		Soil	Vegetative mass	
Phosphorus (P)	mg/kg	125 ± 1.04	0.082 ± 0.004	0.0006
Potassium (K)	mg/kg	110 ± 0.8	0.41 ± 0.01	0.0037
Copper (Cu)	mg/kg	0.191 ± 0.03	3.2 ± 0.5	16.7
Zinc (Zn)	mg/kg	0.701 ± 0.02	9.1 ± 0.2	12.9
Cadmium (Cd)	mg/kg	0.083 ± 0.006	0.0001 ± 0.00004	0.0012
Lead (Pb)	mg/kg	0.765 ± 0.02	0.0012 ± 0.0003	0.0015

The highest content of zinc was observed in the vegetative mass of *Silphium perfoliatum L.* grown on gray forest soils (Table 3).

Thus, the content of zinc in the vegetative mass of *Silphium perfoliatum L.* was higher compared to phosphorus by 59.6 times, potassium by 95.5 times, and copper by 1.96 times. The content of lead in the vegetative mass of *Silphium perfoliatum L.* was 10 times higher compared to cadmium. In the increasing sequence, the content of chemical elements in the vegetative mass of *Silphium perfoliatum L.* was as follows: cadmium – lead – potassium – phosphorus – copper – zinc.

The coefficient of accumulation of copper in the vegetative mass of *Silphium perfoliatum L.* was higher compared to phosphorus by 2604 times, potassium by 56.8 times, zinc by 4.3 times, cadmium by 56.8 times, and lead by 48 times (Table 4).

The coefficient of accumulation of lead in the vegetative mass of *Silphium perfoliatum L.* was also higher compared to cadmium by 1.18 times. In the increasing sequence, the coefficient of accumulation of chemical elements in the vegetative mass of *Silphium perfoliatum L.* was as follows: cadmium – lead – phosphorus – potassium – zinc – copper.

A similar trend in the content of some chemical elements was observed in the vegetative mass of *Sida hermaphrodita L. Rusby*. That is, the highest content was found for zinc.

Thus, the content of zinc in the vegetative mass of *Sida hermaphrodita L. Rusby* was higher compared to phosphorus by 93 times, potassium by 103.3 times and copper by 2.16 times. The cadmium content was 1.3 times higher compared to lead (Table 5). As a result of the analysis of the indicators,

Table 3. Content of chemical elements in the vegetative mass of *Silphium perfoliatum L.*, (n = 4, M ± m)

Indicators	Unit of measurement	Content of substances in the vegetative mass				On average for the options
		I	II	III	IV	
Phosphorus (P)	mg/kg	0.28	0.33	0.34	0.33	0.32 ± 0.07
Potassium (K)	mg/kg	0.19	0.21	0.21	0.19	0.20 ± 0.02
Copper (Cu)	mg/kg	9.4	10.0	9.5	9.9	9.7 ± 0.15
Zinc (Zn)	mg/kg	18.7	19.2	19.3	19.2	19.1 ± 0.21
Cadmium (Cd)	mg/kg	0.00008	0.00011	0.00012	0.00009	0.0001 ± 0.00002
Lead (Pb)	mg/kg	0.0011	0.0012	0.0009	0.0008	0.001 ± 0.00025

Table 4. The coefficient of accumulation of chemical elements in the vegetative mass of *Silphium perfoliatum L.*

Indicators	Unit of measurement	Actual concentration		Accumulation factor
		Soil	Vegetative mass	
Phosphorus (P)	mg/kg	131 ± 4.1	0.32 ± 0.07	0.0024
Potassium (K)	mg/kg	180 ± 1.7	0.20 ± 0.02	0.0011
Copper (Cu)	mg/kg	0.195 ± 0.014	9.7 ± 0.15	62.5
Zinc (Zn)	mg/kg	1.303 ± 0.31	19.1 ± 0.21	14.6
Cadmium (Cd)	mg/kg	0.092 ± 0.0014	0.0001 ± 0.00002	0.0011
Lead (Pb)	mg/kg	0.745 ± 0.012	0.001 ± 0.00025	0.0013

Table 5. Content of chemical elements in the vegetative mass of *Sida hermaphrodita (L.) Rusby*, (n = 4, M ± m)

Indicators	Unit of measurement	Content of substances in the vegetative mass				On average for the options
		I	II	III	IV	
Phosphorus (P)	mg/kg	0.11	0.09	0.12	0.08	0.10 ± 0.091
Potassium (K)	mg/kg	0.095	0.094	0.087	0.087	0.09 ± 0.029
Copper (Cu)	mg/kg	4.37	4.35	4.26	4.25	4.3 ± 0.11
Zinc (Zn)	mg/kg	9.0	9.4	9.4	9.37	9.3 ± 0.22
Cadmium (Cd)	mg/kg	0.00137	0.00134	0.00125	0.00122	0.0013 ± 0002
Lead (Pb)	mg/kg	0.0012	0.0011	0.00092	0.00098	0.001 ± 0.00015

a tendency towards an increase in the accumulation of chemical elements in the vegetative mass of *Sida hermaphrodita L. Rusby* was noted in the following sequence: lead – cadmium – phosphorus – potassium – copper – zinc.

The coefficient of accumulation of chemical elements in the vegetative mass of *Sida hermaphrodita L. Rusby* was the highest for copper compared to phosphorus by 72,500 times, potassium by 92,272 times, zinc by 6.7 times, cadmium by 20.3 times, and lead by 29,000 times (Table 6).

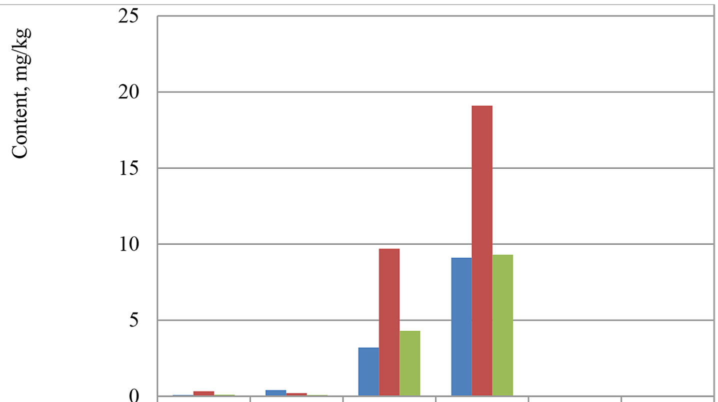
The coefficient of accumulation of cadmium in the vegetative mass of *Sida hermaphrodita L. Rusby* was 20 times higher compared to lead. According to the increasing value of the coefficient of accumulation of chemical elements in the vegetative mass of *Sida hermaphrodita L. Rusby*, the following sequence was observed: potassium - phosphorus - lead - cadmium - zinc - copper.

Analyzing the content of chemical elements in the vegetative mass of energy crops grown on gray forest soils (Fig. 1), it is necessary to note significant differences. It was found that the highest content of phosphorus, copper and zinc was observed in the vegetative mass of *Silphium perfoliatum L.*, potassium and lead - in the vegetative mass of *Miscanthus*, cadmium - in the vegetative mass of *Sida hermaphrodita L. Rusby*. Thus, the phosphorus content in the vegetative mass of *Silphium perfoliatum L.* was 3.9 times higher compared to *Miscanthus* and 3.2 times higher compared to *Sida hermaphrodita L. Rusby*. The content of potassium in the vegetative mass of *Miscanthus* was higher compared to *Silphium perfoliatum L.* by 1.86 times and *Sida hermaphrodita L. Rusby* by 4.5 times. The content of copper in the vegetative mass of *Silphium perfoliatum L.* was 3.03 times higher than that of *Miscanthus* and 3.25 times higher than that of *Sida hermaphrodita L. Rusby*. The content of zinc in the vegetative mass of *Silphium perfoliatum L.* was 2.1 times higher compared to *Miscanthus* and 2.05 times *Sida hermaphrodita L. Rusby*. The content of cadmium in the vegetative mass of *Sida hermaphrodita L. Rusby* was 1.3 times higher compared to *Miscanthus* and 1.3 times *Silphium perfoliatum L.* The content of lead in *Miscanthus* was 1.2 times higher compared to *Silphium perfoliatum L.* and 1.2 times higher than *Sida hermaphrodita L. Rusby*.

According to the results of research, it was established (Fig. 2) that the highest accumulation coefficient in the vegetative mass of *Silphium perfoliatum L.* was observed for phosphorus, copper, and zinc, in the vegetative mass of *Miscanthus* for potassium and lead, and in the vegetative mass of *Sida hermaphrodita L. Rusby*, respectively, for cadmium.

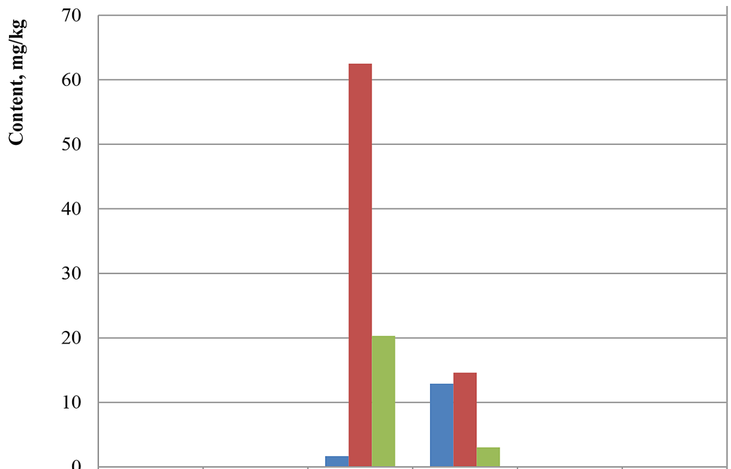
Table 6. The coefficient of accumulation of chemical elements in the vegetative mass of *Sida hermaphrodita (L.) Rusby*

Indicators	Unit of measurement	Actual concentration		Accumulation factor
		Soil	Vegetative mass	
Phosphorus (P)	mg/kg	350 ± 1.6	0.10 ± 0.091	0.00028
Potassium (K)	mg/kg	400 ± 1.2	0.09 ± 0.0029	0.00022
Copper (Cu)	mg/kg	0.211 ± 0.03	4.3 ± 0.11	20.3
Zinc (Zn)	mg/kg	3.063 ± 0.07	9.3 ± 0.22	3.03
Cadmium (Cd)	mg/kg	0.093 ± 0.002	0.0013 ± 0.0002	0.014
Lead (Pb)	mg/kg	1.415 ± 0.04	0.001 ± 0.00015	0.0007



	Phosphorus (P)	Potassium (K)	Copper (Cu)	Zinc (Zn)	Cadmium (Cd)	Lead (Pb)
Miscanthus	0,082	0,41	3,2	9,1	0,0001	0,0012
Silphium perfoliatum L.	0,32	0,2	9,7	19,1	0,0001	0,001
Sida hermaphrodita (L.) Rusby	0,1	0,09	4,3	9,3	0,0013	0,001

Figure 1. Comparative assessment of the content of chemical elements in the vegetative mass of various energy crops



	Phosphorus (P)	Potassium (K)	Copper (Cu)	Zinc (Zn)	Cadmium (Cd)	Lead (Pb)
Miscanthus	0,0006	0,0037	1,67	12,9	0,0012	0,0015
Silphium perfoliatum L.	0,0024	0,0011	62,5	14,6	0,0011	0,0013
Sida hermaphrodita (L.) Rusby	0,00028	0,00022	20,3	3,03	0,014	0,0007

Figure 2. Comparative assessment of the coefficient of accumulation of chemical elements in the vegetative mass of various energy crops

Thus, the coefficient of phosphorus accumulation in the vegetative mass of *Silphium perfoliatum L.* was 4.0 times higher compared to *Miscanthus* and 8.5 times higher compared to *Sida hermaphrodita L. Rusby*. The coefficient of potassium accumulation in the vegetative mass of *Miscanthus* was 3.3 times higher compared to the similar raw material obtained from *Silphium perfoliatum L.* spp. and 16.8 times *Sida hermaphrodita L. Rusby*. The coefficient of accumulation of copper and zinc in *Silphium perfoliatum L.* was higher compared to *Miscanthus* by 3.7 times and 1.13 times and *Sida hermaphrodita L. Rusby* by 3.07 times and 4.8 times, respectively.

The coefficient of accumulation of cadmium in the vegetative mass of *Sida hermaphrodita L. Rusby* was 11.6 times higher compared to *Miscanthus* and 12.7 times *Silphium perfoliatum L.*. The coefficient of lead accumulation was higher in the vegetative mass of *Miscanthus* by 1.15 times compared to *Silphium perfoliatum L.* and by 20 times compared to *Sida hermaphrodita L. Rusby*.

DISCUSSION

According to the analysis of literary primary sources revealed (Razanov et al., 2023, Razanov et al., 2024) that during the cultivation of energy crops in the territories of man-made load due to the accident at the Chernobyl nuclear power plant on turf-podzolic soils in the conditions of Polissia, a high level of accumulation of Pb in the vegetative mass is observed, in particular, in *Silphium perfoliatum L.* 2.65 mg/kg to 2.89 mg/kg, Cd – from 0.234 mg/kg to 0.253 mg/kg, Zn – from 32.83 mg/kg to 34.50 mg/kg and Cu – from 5.60 mg/kg to 5.79 mg/kg.

According to our research conducted under the conditions of anthropogenic impact of intensive agriculture on grey forest soils in the Western Forest-Steppe of Ukraine, it was found that the content of phosphorus in the vegetative mass of energy crops (*Miscanthus*, *Silphium perfoliatum L., Sida hermaphrodita L. Rusby*) grown in the conditions of gray forest soils of the Western Forest-steppe of Ukraine ranged from 0.082 mg/kg to 0.32 mg/kg, potassium – from 0.09 mg/kg kg to 0.41 mg/kg, copper – from 3.2 mg/kg to 9.7 mg/kg, zinc – from 9.1 mg/kg to 19.1 mg/kg, cadmium – from 0.0001 mg /kg to 0.0013 mg/kg and lead – from 0.001 mg/kg to 0.0012 mg/kg.

A high content of Zn and Cu was found in the vegetative mass of *Silphium perfoliatum L.*. In particular, the content of Zn and Cu in the vegetative mass of *Silphium perfoliatum L.* was higher compared to *Miscanthus* by 2.1 times and 3.03 times and to *Sida hermaphrodita L. Rusby* – by 2.05 times and 3.2 times, respectively. Along with this, the highest coefficient of accumulation of Zn and Cu in the vegetative mass of *Silphium perfoliatum L.* was found, which was 14.6 and 62.5 units, respectively.

The highest content of phosphorus, copper, and zinc in the vegetative mass of *Silphium perfoliatum L.*, which was 0.32 mg/kg, 9.7 mg/kg, and 19.1 mg/kg, respectively, and potassium and lead in the vegetative mass of *Miscanthus*, which was within 0.41 mg/kg and 0.0012 mg/kg, respectively, for cadmium in the vegetative mass of *Sida hermaphrodita L. Rusby*, in particular 0.0013 mg/kg.

The coefficient of accumulation in the vegetative mass of energy crops (*Miscanthus*, *Silphium perfoliatum L., Sida hermaphrodita L. Rusby*) was in the range of phosphorus from 0.0028 to 0.0024, potassium – from 0.00022 to 0.0037, copper – from 16.7 to 62, 5, zinc – from 3.03 to 14.6, cadmium – from 0.011 to 0.014 and lead – from 0.0007 to 0.0015. The highest coefficient of accumulation of phosphorus, copper and zinc was found in the vegetative mass of *Silphium perfoliatum L.* – 62.5 and 14.6, respectively, potassium and lead in the vegetative mass of *Miscanthus* – 0.0037 and 0.0015, respectively, and cadmium – in the vegetative mass of *Sida hermaphrodita L. Rusby*, in particular 0.014.

CONCLUSIONS

Based on the results of research, it was found that *Miscanthus*, *Silphium perfoliatum L.* and *Sida hermaphrodita (L.) Rusby*, grown on gray forest soils in the conditions of Western Forest Steppe of Ukraine, are characterized by different levels of accumulation in the vegetative mass of chemicals, in particular, P, K, Su, Zn, Cd, Pb. Thus, the highest level of accumulation of phosphorus (0.32 mg/kg), copper (9.7 mg/kg) and zinc (19.1 mg/kg) was found in the vegetative mass of *Silphium perfoliatum L.* The highest level of accumulation of potassium (0.41 mg/kg) and lead (0.0012 mg/kg) was found in the vegetative mass of *Miscanthus*. The highest level of accumulation of cadmium (0.0013 mg/kg) was found in the vegetative mass of *Sida hermaphrodita L. Rusby*.

When using the vegetative mass of energy crops as biofuel, special attention should be focused on controlling the entry of copper and zinc into the environment. When transferring soil to the field crop rotation for the cultivation of agricultural crops (after the end of the period of energy crops cultivation), it is necessary to control the provision of the need for Zn and Cu for these plants.

REFERENCES

1. Branitsky Yu.Yu., Mazur O.V., Alieksieiev O.O. 2019. The influence of technological methods of cultivation on the yield of vine-shaped millet in the first year of vegetation. Agriculture and forestry, 13, 68–83. doi: 10.37128/2707-5826-2019-2-7 (in Ukrainian).
2. Branitskyi Y., Telekalo N., Kupchuk I., Mazur O., Alieksieiev O., Okhota Y., Mazur O. 2022. Improvement of technological methods of switchgrass (Panicum virgatum L.) growing in the Vinnytsia region. Acta Fytotechnica et Zootechnica, 25(4), 311–318. doi: 10.15414/afz.2022.25.04.311-318.
3. Didenko N., Mosiichuk Ya., Islam R., Zosymchuk M., Mazurenko B., Lavrenko S., Kharytonov M., Babenko M. 2023. Prospect of growing energy crops

on biosolids-amended marginal soils in Ukraine. Advances in Transdisciplinary Engineering, 38, 875–8825. doi: 10.3233/ATDE230371

4. Dovhalyuk A. 2013. Environmental pollution with toxic metals and its indication using plant test systems. Biological studies, 1, 197–204 (in Ukrainian).
5. Dydiv A., Piddubna A., Gucol G., Vradii O., Zhylishchych Y., Titarenko O., Razanova A., Odnosum H., Postoienko D., Kerek S. 2023. Accumulation of lead and cadmium by vegetables at different levels of gray forest soil moistening in the conditions of the Right Bank Forest Steppe of Ukraine. Journal of Ecological Engineering, 24(10), 198–204. doi: 10.12911/22998993/170291.
6. DSTU 4770.1:2007 – DSTU 4770.9:2007. Soil quality. Determination of the content of mobile manganese compounds (zinc, cadmium, iron, cobalt, copper, nickel, chromium, lead) in the soil in a buffered ammonium-acetate extract with pH 4.8 by the method of atomic absorption spectrophotometry. [Effective from 01.01.2009]. K.: Derzhspozhivstandard of Ukraine 2009. 117 (in Ukrainian).
7. Gumentyk M.Ya., Chernysky V.V., Gumentyk V.M., Kharytonov M.M. 2020. Technology for two switchgrass morphotypes growing in the conditions of Ukraine's forest Steppe zone. INMATEH - Agricultural Engineering, 61(2), 71–76. doi: 10.35633/inmateh-61-08
8. Holovach O., Kozlovskyi V., Demkiv O. 2004. Contamination of agricultural soils with heavy metals and the nature of their redistribution in corn plants. Bulletin of Lviv University. Biological series, 38, 205–210 (in Ukrainian).
9. Honcharuk I., Babyna O. 2020. Dominant trends of innovation and investment activities in the development of alternative energy sources. Wschodnioeuropejskie Czasopismo Naukowe (East European Scientific Journal), 2(54), 6–12.
10. Kaletnik G., Honcharuk I., Okhota Y. 2020. The waste-free production development for the energy autonomy formation of ukrainian agricultural enterprises. Journal of Environmental Management & Tourism, 11, 3(43), 513–522. doi: 10.14505/jemt.v11.3(43).02.
11. Kaletnik G., Prutska O., Pryshliak N. 2014. Resource potential of bioethanol and biodiesel production in Ukraine. Visegrad Journal on Bioeconomy and Sustainable Development, 3, 1, 9–12. doi: 10.2478/vjbsd-2014-0002.
12. Kaletnik G., Pryshliak N. 2019. Bioenergy potential development of the agrarian sector as a component of sustainable development of Ukraine. Management mechanisms and development strategies of economic entities in conditions of institutional transformations of the global environment: col. monog. ISMA University. Riga: Landmark SIA, 96–104.
13. Kaletnik G., Pryshliak N., Tokarchuk D. 2021. Potential of production of energy crops in ukraine and their processing on solid biofuels. Ecological Engineering & Environmental Technology, 22(3), 59–70. doi: 10.12912/27197050/135447.
14. Kaletnik H., Pryshliak V., Pryshliak N. 2020. Public policy and biofuels: energy, environment and food trilemma. Journal of Environmental Management & Tourism, 10, 4(36), 479–487. doi:10.14505/jemt.v10.3(35).01.
15. Kharytonov M., Babenko M., Martynova N., Klimkina I.,Wiche O., Heilmeier H. 2023. Elemental composition of Miscanthus biomass grown on different kinds of Technosols. International Journal of Environmental Studies, 80, 2, 488–496. doi: 10.1080/00207233.2022.2152624.
16. Kharytonov M., Klimkina I.; Martynova N.; Rula I. Gispert M., Pardini G. 2021. Estimation of the biochar effect on annual energy crops grown in post-mining lands. Ecological Engineering and Environmental Technology, 22, 2, 15–26. doi: 10.12912/27197050/133257.
17. Kharytonov M., Martynova N., Babenko M., Kovrov O., Frolova L., González P. 2024. Application of flocculated sewage sludge for growing miscanthus on post-mining lands 81, 1, 403–419. doi: 10.1080/00207233.2023.2262867.
18. Kharytonov M., Martynova N., Babenko M., Rula I., Gumentyk M., Bagorka, M., Pashova V. 2019. The production of biofuel feedstock on reclaimed land based on sweet sorghum biomass. Agriculture and Forestry, 65, 4, 233 – 240. doi: 10.17707/AgricultForest.65.4.21.
19. Kharytonov M., Martynova N., Babenko M., Rula I., Ungureanu N., Ștefan V. 2023. Production of sweet sorghum bio-feedstock on technosol using municipal sewage sludge treated with flocculant in Ukraine. Agriculture (Switzerland), 3, 6. doi: 10.3390/agriculture13061129.
20. Kharytonov M., Martynova N., Holoborodko K., Babenko M., Alexeyeva A., Zhukov O. 2019. Photosynthetic activity of sweet sorghum fertilised by sewage sludge. International Journal of Environmental Studies, 81, 1, 420–431. doi: 10.1080/00207233.2023.2287346.
21. Kharytonov M., Martynova N., Tokar A., Rula I., Babenko M., Bagorka M. 2019. Sweet sorghum biomass quantitative and qualitative characteristic depending on hybrid and type of soil. INMATEH - Agricultural Engineering, 59, 3, 189–196. doi: 10.35633/INMATEH-59-21.
22. Kharytonov M., Pidlisnyuk V. Stefanovska T. Babenko M. Martynova N. Rula I. 2019. The estimation of Miscanthus giganteus adaptive potential for cultivation on the mining and post-mining lands in Ukraine. Environmental Science and

Pollution Research, 26, 3, 2974–2986. doi: 10.1007/s11356-018-3741-0.

23. Kozlovsky V., Romaniuk N., Terek O., Chonka I., Kolesnyk O., Bolashi Sh., Boyko N. 2005. Heavy metals in soils and plants of the Tisza river floodplain. Herald of Lviv University. Biological series, 40. 35–50.
24. Kulyk M., Kalynychenko O, Pryshliak N., Pryshliak V. 2020. Efficiency of using biomass from energy crops for sustainable bioenergy development. Journal of Environmental Management & Tourism, 11, 5. 1040-1053. doi: 10.14505/jemt.v11.5(45).02.
25. Kuraeva I.V., Roga I.V., Sorokina L.Yu., Golubtsov O.G. 2012. Assessment of the content of heavy metals and their migration conditions in the agricultural landscapes of the Ternopil region. Ukrainian Geographical Journal, 3, 25.
26. Lopushniak V., Hrytsuliak H., Gumentyk M., Kharytonov M., Barchak B., Jakubowski T. 2021. The formation of the leaf surface area and biomass of the miscanthus giganteus plants depending on the sewage sludge rate. E3S Web of Conferences, 28030. doi: 10.1051/e3sconf/202128006009.
27. Lopushniak V., Tonkha O., Hrytsuliak H. 2022. Productivity models of herbal bioenergy cultures depending on biometric indicators of overhead mass. Ecological Engineering & Environmental Technology, 23(2), 162–172. doi: 10.12912/27197050/145731.
28. Mykolenko S., Tymchak D., Tchoursinov Yu., Kharytonov M. 2022. Microwave popping characteristics, chemical composition and microstructure of sorghum grain. INMATEH - Agricultural Engineering, 67, 2, 191–200. doi: 10.35633/inmateh-67-19.
29. Palamarchuk V., Honcharuk I., Honcharuk T., Telekalo N. 2018. Effect of the elements of cultivation technology on bioethanol production under conditions of the right-bank forest-steppe of Ukraine. Ukrainian Journal of Ecology, 8(3), 47–53.
30. Pryshliak N., Tokarchuk D. 2020. Socio-economic and environmental benefits of biofuel production development from agricultural waste in Ukraine. Environmental & Socio-economic Studies, 8, 1, 18–27. doi: 10.2478/environ-2020-0003.
31. Razanov S., AlieksieievO., Alieksieieva O., Vradii O., Mazur K., Puyu V., Piddubna A., Povoznikov M., Postoienko D., Zelisko O. 2024. The content of heavy metals and trace elements in different soils used under the conditions of homestead plots and field agricultural lands of Ukraine. Journal of Ecological Engineering, 25(6), 42–50. doi: 10.12911/22998993/186820.
32. Razanov S., Husak O., Hnativ P., Dydiv A., Bakhmat O., Stepanchenko V., Pryshchepa A., Shcherbachuk V., Mazurak O. 2023. The influence of the gray forest soil moisture level on the accumulation of Pb, Cd, Zn, Cu in spring barley grain. Journal of Ecological Engineering, 24(7), 285–292. doi: 10.12911/22998993/164747.
33. Razanov S., Melnyk V., Symochko L., Dydiv A., Vradii O., Balkovskyi V., Khirivskyi P., Panas N., Lysak H., Koruniak O. 2022. Agroecological assessment of gray forest soils under intensive horticulture. International Journal of Ecosystems and Ecology Science (IJEES), 12(4), 459–464. doi: 10.31407/ijees12.4.
34. Razanov S., Piddubna A., Gucol G., Symochko L., Kovalova S., Bakhmat, M., Bakhmat O. 2022. Estimation of heavy metals accumulation by vegetables in agroecosystems as one of the main aspects in food security. International Journal of Ecosystems and Ecology Science (IJEES), 12(3), 159–164. doi: 10.31407/ijees12.320.
35. Razanov S., Tkachuk O., Lebedieva N., Shkatula Yu., Polishchuk M., Melnyk M., Krektun B., Razanova A. 2023. Phytoremediation of heavy metal contamination by perennial legumes. International Journal of Environmental Studies, 81(1). 216–222. doi: 10.1080/00207233.2023.2296764.
36. Zulauf C., Prutska O., Kirieieva E., Pryshliak N. 2018. Assessment of the potential for a biofuels industry in Ukraine. Problems and Perspectives in Management, 16, 4, 83–90. doi: 10.21511/ppm.16(4).2018.08.