EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

*Ecological Engineering & Environmental Technology* 2023, 24(3), 201–211
https://doi.org/10.12912/27197050/160095
ISSN 2719-7050, License CC-BY 4.0

Received: 2022.12.04
Accepted: 2023.01.27
Published: 2023.02.25

# Indices of Soil and Plant Cover Pollution Due to Re-Introduction of Sediment Water Under the Energy Willow on Aluvisol of Ukraine

Vasyl Lopushniak[1], Halyna Hrytsuliak[2*], Tomasz Jakubowski[3], Yurii Voloshyn[2], Krystyna Karavanovych[2], Taras Kachala[2]

[1] National University of Life and Environmental Sciences of Ukraine, Heroyiv Oborony St. 15, Kyiv, 03041, Ukraine
[2] Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska St. 15, Ivano-Frankivsk, 76019, Ukraine
[3] Hugo Kollataj University of Agriculture in Krakow, 31-120, 21 Mickiewicz Ave., Krakow, Poland
* Corresponding author's e-mail: gritsulyaka@ukr.net

**ABSTRACT**
Municipal sewage sludge is considered as an important resource for replenishing organic carbon and mineral nutrition elements in the soil. However, its widespread use in the agricultural sector is associated with the risks of soil contamination by pollutants, in particular heavy metals, and their inclusion in trophic food chains. A relatively ecologically safe way to dispose of sewage sludge is to apply it to energy crops.In order to study the influence of sewage sludge application on the ecological condition of podzolic soil and the level of heavy metal contamination of plant cover, research was carried out in the Transcarpathian region of Ukraine on a willow plantation of the second cycle of energy use and repeated application of fresh sewage sludge and its composts with coniferous sawdust and grain straw cultures in different doses.Research has established that under the influence of the application of sewage sludge, the indicators of the content of heavy metals in the roots and above-ground shoots of energy willow significantly changed. The highest doses of sewage sludge of 60–80 t/ha led to a significant increase in the content of As, Mo, and Pb compared to other research options. The content of Fe, Zn, Sr, Y in these options was at the level of the option where compost was applied (sewage sludge + straw (3:1) + cement dust 10%) – 40 t/ha. Also, the use of cement dust in this version led to the highest Nb content. Ni, Cu.An increase in the content of heavy metals in the soil led to an increase in the translocation of heavy metals in energy willow plants. Application of the highest dose of sewage sludge in the experiment –80 t/ha (option 5) caused the highest translocation coefficients of Fe, Nb, Rb, Y, Mo. And the highest values of Sr, As, Pb translocation coefficients were noted in option 10, where compost was applied (sewage sludge + straw (3:1) + cement dust 10%) – 40 t/ha, which indicates a significant influx of cement dust into the accumulation of these dangerous metals in plants. The highest value of the Integral index of energy willow plant pollution – 222 was recorded in the variant where fresh sewage sludge was applied at the rate of 80 t/ha, which was 17–20 points higher than the values of the closest variants of the experiment.

**Keywords:** heavy metals, biological absorption coefficient, translocation coefficient, intra-tissue contamination index, integral contamination index.

## INTRODUCTION

The global problem of environmentally safe disposal of wastewater and its sediment (SS) is caused by the general urbanization of the planet, the constantly growing volumes of municipal waste. Excessive use of natural resources determines the importance of finding ways to effectively reuse water and nutrients contained in wastewater and its sediment. All over the world,SS is considered as an important resource for use in the agricultural sector [Kumar V., Chopra A., Kumar A., 2017; Kirchmann H., Börjesson G., Kätterer T. et al., 2017]. The value of SS is related to the content of biogenic substances in it, primarily nitrogen and phosphorus,carbon compounds. Owing to the relatively high content of basic nutrients and certain microelements in

SS, the method of its disposal through application as a fertilizer for growing cultivated plants is becoming more and more widespread in world practice. Many researchers note the significant impact of SS application on the physicochemical, agrochemical, and ecological properties of the soil, the change in the chemical composition of cultivated plants, and the recirculation of nutrient compounds in agroecosystems [Eid E.M., Alamri S.A.M., Shaltout K.H. et al., 2020; Skrylnyk Ye.V. Maksymenko N.V., RyzhkovaYa.S. et al., 2020; Buta M., Hubeny J., Zieliński W. et al., 2021].

Although the use of SS to add nutrients and organic compounds can be beneficial to the soil, it also poses risks due to the content of pollutants such as heavy metals, organic compounds and pathogens [Lamastra L., Suciu N.A., Trevisan M., 2018; Pöykiö R., Watkins G., Dahl O., 2019], which can serve as an additional source of pollution of agroecosystems and inclusion of pollutants in trophic food chains. Soil degradation due to increased metal content is considered a serious threat to soil quality and human health [Golui, D., Datta, S.P., Dwivedi, 2019; Kalenska S. et al., 2021].

Knowing the total content of heavy metals in SS does not mean the danger they may pose. The toxicity of metals largely depends on their mobility and bioavailability [Latosińska J, Kowalik R, Gawdzik J. et al., 2021]. In studies by Wydro U., Jabłońska-Trypuć A., Hawrylik E. et al., (2021) the introduction of SS caused the immobilization of heavy metals from the soil.

Agricultural use of SS contributes to the spread of new pollutants in the environment, which can lead to food contamination [Buta M., Hubeny J., Zieliński W. et al., 2021], and also contribute to the spread of organic pollutants in the soil, which represents a direct environmental risk [Pulkrabová J., Černý J., Száková J. et al., 2019]. Adding SS to the soil can suppress the development of soil microflora and mesofauna, negatively affects the microbiome and resistome [Markowicz A., Bondarczuk K., Wiekiera A. et al., 2021]. Researchers note that SS may contain pharmaceuticals in different concentrations, and the presence of these micropollutants negatively affects the environment [Bolesta W., Głodniok M., Styszko K., 2022].

Hazardous substances in SS can threaten agro-ecosystems and food safety [Rivier P.-A., Havranek I., Coutris C., et al., 2019]. Long-term use of SS can significantly increase the concentration of pollutants, causing hyperaccumulation of certain compounds or phytotoxicity in cultivated crops [Nunes N., Ragonezi C., Gouveia C., et al., 2021]. Also, the introduction of SS can import a significant amount of microplastics into the soil, which can accumulate and affect the properties of the soil, as well as migrate along the soil profile, causing pollution of deep soil layers and groundwater [Ding Gao, Xin-yu Li, Hong-tao Liu., 2020]. According to the research of A. Lutskevich, the leaching of nitrate and ammonium compounds N, Ni and Cd from the introduced SS can migrate to a depth of more than 0.8 m and contribute to the pollution of aquifers [Luczkiewicz A., 2006].

Thus, there are two conflicting points of view in approaches to wastewater management. The first considers SS as a source of nutrients and organic matter for use as fertilizers to restore fertility, revitalize polluted areas and create anthropo-soils.

On the other hand, CO is considered a potential source of soil pollution by pollutants of various nature, pathogens, polycyclic aromatic hydrocarbons, biocides, care products and their residues, synthetic hormones, microplastics, end products of the life cycle of nano- and biotechnologies, highly specific microorganisms [Rorat A., Courtois P., Vandenbulcke F., et al., 2019].

Combining the cultivation of biomass from fast-growing wood with municipal wastewater disposal can be a promising solution to several economic, energy and environmental problems [Tsvetkov I., Elmi A., Al-Khaldy A., Al-Olayan M., 2020; Ronald C. Sims, Sean K. Bedingfield, Reese Thompson et al., 2016; Tzvetkova N., Marinova, S., 2021].

Biomass is considered by many scientists as the only source of renewable energy that can replace oil-based liquid transportation fuel in the near future, and wastewater and its sediment are considered an important potential resource that can be used to produce biomass for energy purposes [Sims R., Bedingfield S., Thompson, R. et al., 2016; Wójcik, M., Stachowicz, F., 2018].

The use of SS as a fertilizer for technical or energy crops is considered the safest and most economically feasible method of its disposal. An example of this can be energy willow, which is not only a good source of biomass, but can also be used for phytoremediation of territories polluted by pollutants, able to remove dangerous substances from a polluted environment [Panasiewicz K., Niewiadomska A., Sulewska H. et al., 2019].

The use of SS for the conditioning of agricultural areas can be an alternative way of its proper utilization and increase of soil fertility. But the content of certain toxic compounds and pathogenic microorganisms limits its use. By applying different doses of SS, it was observed that various soil parameters changed significantly compared to the untreated control soil. The content of total organic carbon (C) and nitrogen (N) increased up to the application of 50 t ha-1 of SS.

As a result, this led to a significant increase in microbial biomass, an increase in soil enzymes - phosphatase, dehydrogenase, urease. The application of SS also increased the available forms of heavy metals (Ni, Cr, Pb, Cu and Cd) in the soil, but below the threshold values [Dhanker R., Chaudhary S., Goyal S.et al., 2021].

The use of SS has considerable advantages during the cultivation of bioenergy crops, remediation of degraded lands. Although this measure should also be evaluated in terms of energy security [Nunes N., Ragonezi C., Gouveia C. et al., 2021]. In the research of Skowrońska M. et al., 2020, a significant dose-dependent increase in the content of C and N, as well as the activity of soil enzymes, as well as the activity of soil enzymes, was observed when applying 10–60t of SS in terms of dry matter to the herbaceous energy crop *Phalaris arundinacea*. Such standards contribute to the long-term impact on soil quality indicators and do not pose a risk for the accumulation of heavy metals and surface-active substances [Skowrońska M., Bielińska E., Szymański K. et al., 2020]. The use of energy willow plantations for SS utilization is a balanced way to treat municipal wastewater and sludge, potentially reducing environmental risks and economic burden compared to conventional treatment. However, the function of forming the potential of willow biomass from the application of SS has not yet been fully established [Sas E., Hennequin, L.M., Frémont A. et al., 2021; Wolna-Maruwka A., Sulewska H., Niewiadomska, A. et al., 2018]. Currently, active research is being conducted in various parts of the world on the effective use of SS under energy willow.Currently, active research is being conducted in various countries on the effective use of SS under energy willow, in particular in Poland, Sweden, Turkey and others. Active research is currently underway. Also, technical solutions are being developed for the repeated subsurface application of SS in the plantation of energy willow [Stachowicz F., Trzepieciński T., Wójcik M. et al., 2016]. In willow plantations, after harvesting biomass, after repeated application of SS, plant survival, height growth intensity, net photosynthetic productivity, permeability through leaf stomata and transpiration, as well as the number of regrown shoots in plants significantly increase [Wolna-Maruwka A., Sulewska H., Niewiadomska, A. et al., 2018]. The issue of safe dosing of the introduced SS remains unexplored, since it is the dose that is the factor of contamination of the soil environment. Long-term field research is needed on the ecologically safe use of sewage sludge [Hoang S.A., Bolan N., Madhubashani A.M.P. et al., 2022], including for energy crops.The aim of research was to evaluate the effect of repeated application of SS in energy willow plantations on complex heavy metal contamination of podzolic soil in the foothills of the Carpathians of Ukraine.

The study involved the implementation of the following tasks:

- determination of the mass fraction of chemical elements, in particular heavy metals, in the soil, underground and above-ground organs of the energy willow during the repeated (second) cycle of plantation use under the influence of different norms of SS and their composts with organic materials (sawdust of coniferous trees and straw of grain crops;
- determination of the coefficients of biological absorption of heavy metals, the Index of intra-tissue pollution and the coefficients of translocation of heavy metals at different doses of the use of SS and composts made on the basis of SS and sawdust of coniferous trees or straw of grain crops;
- calculation of the Integral indicator of vegetation cover pollution and assessment of the polluting effect of various norms of SS and composts with organic materials re-introduced under the energy willow plantation.

## MATERIALS AND METHODS

An experimental plantation of energy willow was created in the early spring period in the spring of 2011 at the collection and research field of the Ivano-Frankivsk Vocational College of the Lviv National University of Nature Management in the village of Chukalivka, Ivano-Frankivsk Territorial Community, Ivano-Frankivsk District, Ivano-Frankivsk Oblast. The width of the experimental area was 4.0 m; length – 7.0 m; registered area – 28.0 $m^2$. The total area of the experimental site is 54 $m^2$. Repetition is three times, placement of plots is systematic [Lopushnyak V., Hrytsulyak G., 2014].

Options of the experiment: 1. Control – withoutfertilizers; 2. Mineral fertilizers – $N_{00}P_{100}K_{100}$; 3. SS – 40 t/ha; 4. SS – 60 t/ha; 5. SS – 80 t/ha; 6. Compost (SS+ sawdust (3:1)) – 60 t/ha; 7. Compost (SS + straw (3:1)) – 20 t/ha; 8. Compost (SS + straw (3:1)) – 40 t/ha; 9. Compost (SS + straw (3:1)) – 60 t/ha; 10. Compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha [Lopushnyak V., Hrytsulyak G., 2014; Lopushniak, V., Hrytsuliak, H., Gamayunova et al., 2022; Lopushniak V., Gritsulyak G., Yakubovsky T. et al., 2020].

Field and laboratory studies of energy willow plantations of the full cycle of use (after one cycle of growing and harvesting biomass) were carried out according to methods accepted in agronomy. The research was carried out in a field experiment during 2016 – 2021 after one cycle of growing and harvesting energy willow biomass [Korsun S.H., Klymenko I.I., Bolokhovs′ka V.A. et al., 2019; Rybalova O., Bryhada O., Sarapina M., 2020; Rybalova O.V., Korobkina K.M., 2017]. After the creation of experimental plantations, the four-year-old willow was cut in autumn so that 8–10 cm of the trunk remained above the soil surface. The following year, after cutting the vegetative mass in early spring, after the cessation of persistent frosts, loosening of the soil was carried out between the rows with an improved milling cultivator, as well as sewage sludge and composts based on sewage sludge. and sawdust of coniferous trees, straw of grain crops were repeatedly applied according to the specified scheme of the experiment [Hryshko V. M., Piskova O. M., 2014; Lopushnyak, V., Hrytsulyak, H., Voloshin, Y. et al., 2022; Mosquera-Losada R., Amador-García A., Muñóz-Ferreiro N. et al., 2017].

Appropriate work was carried out in the first year to ensure the vitality of the plants. In the first year after felling, 5–8 branches with a length of about 3–4 m sprout from one trunk. The length of the branches depends on the water regime and the level of mineral nutrition. After the end of the fourth year of vegetation, the willow was cut by hand and samples were taken for quantitative analyzes [Korsun S.H., Klymenko I.I., Bolokhovs′ka V.A. et al.,2019; Lopushniak V., Gritsulyak G., Yakubovsky T. et al., 2020].

In the specified layer (0–20 cm), soil samples were taken, as well as samples of vegetative mass (leaves and shoots) and root system were taken in the summer period, which in the experiment was from June to August. Average values of indicators were determined in the obtained results.

The study of the elemental composition ofaluvisoland plants was carried out by X-ray fluorescence analysis on the EXPERT 3L analyzer [Lopushnyak V., Hrytsulyak G., 2014; Lopushniak, V., Hrytsuliak, H., Gamayunova et al., 2022; Lopushnyak V., Hrytsulyak H., Voloshin Y. et al., 2022]. All experimental measurements on correlation-regression analysis performed using the STATISTICA 6.0 program [Lopushniak V., Gritsulyak G., Yakubovsky T. et al., 2020].

In plant samples, the biological absorption coefficient ($Cba$) the formula 1 [Rybalova, 2020, Sas, 2021].:

$$Cba = \frac{Lx}{Nx} \quad (1)$$

The Index of intra-tissue pollution ($I_{itp}$) of plants the formula 2 [Rybalova, 2020, Sas, 2021], %.

$$I_{itp} = \frac{L_{X_i}}{L_{control}} \quad (2)$$

The coefficients of translocation ($C_t$) the formula 3.

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

The integral indicator ($IS$) of vegetation cover was calculated according to formula 4 [Lopushnyak V., Hrytsulyak, H., Voloshin, Y. et al., 2022; Rybalova O., Bryhada O., Sarapina M., 2020].

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

where: $IS$ – an integral indicator of vegetation cover pollution [Lopushnyak V., Hrytsulyak, H., Voloshin, Y. et al., 2022; Rybalova O., Bryhada O., Sarapina M., 2020].

Thus, the research methods used make it possible to provide a comprehensive assessment of heavy metal contamination of aluvisolwith repeated application of SS as a fertilizer for energy willow.

## RESULTS AND DISCUSSION

Studies indicate certain regularities that are reflected in the change in the content of chemical elements, including heavy metals in plants and their localization in the aluvisol environment, roots and vegetative shoots of energy willow under the influence of the use of SS and its composts (Table 1).

**Table 1.** Mass fraction of individual chemical elements on aluvisol at a depth of 0 – 20 cm (a), roots (b), shoots (c) of energy willow after fertilization based on SS and its composts with organic materials, (average for 2016 – 2021)

| Chemical element | | Research option | | | | | | | | | | LSD 0.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| Fe | *a* | 0.18 | 0.22 | 0.29 | 0.34 | 0.42 | 0.27 | 0.30 | 0.36 | 0.38 | 0.43 | 0.02 |
| | *b* | 0.15 | 0.15 | 0.17 | 0.19 | 0.29 | 0.19 | 0.23 | 0.26 | 0.27 | 0.29 | 0.01 |
| | *c* | 0.19 | 0.25 | 0.31 | 0.37 | 0.44 | 0.34 | 0.37 | 0.41 | 0.39 | 0.44 | 0.01 |
| Zn | *a* | 0.43 | 0.45 | 0.51 | 0.69 | 0.99 | 0.88 | 0.54 | 0.66 | 0.68 | 0.72 | 0.03 |
| | *b* | 0.40 | 0.40 | 0.42 | 0.48 | 0.54 | 0.51 | 0.44 | 0.47 | 0.51 | 0.53 | 0.02 |
| | *c* | 0.46 | 0.48 | 0.53 | 0.75 | 1.01 | 0.83 | 0.59 | 0.69 | 0.71 | 0.81 | 0.02 |
| Sr | *a* | 0.16 | 0.16 | 0.18 | 0.18 | 0.21 | 0.19 | 0.17 | 0.19 | 0.20 | 0.20 | 0.01 |
| | *b* | 0.10 | 0.10 | 0.10 | 0.12 | 0.17 | 0.15 | 0.12 | 0.14 | 0.15 | 0.18 | 0.01 |
| | *c* | 0.19 | 0.20 | 0.20 | 0.24 | 0.27 | 0.24 | 0.20 | 0.23 | 0.25 | 0.30 | 0.01 |
| Nb* | *a* | 11 | 11 | 13 | 16 | 21 | 20 | 15 | 19 | 19 | 22 | 1.26 |
| | *b* | 9 | 10 | 11 | 13 | 18 | 17 | 19 | 24 | 23 | 27 | 1.12 |
| | *c* | 16 | 16 | 20 | 28 | 20 | 19 | 24 | 23 | 27 | 16 | 2.31 |
| As* | *a* | 8 | 8 | 10 | 15 | 23 | 21 | 19 | 18 | 18 | 20 | 1.02 |
| | *b* | 5 | 6 | 11 | 12 | 21 | 15 | 20 | 17 | 15 | 18 | 0.14 |
| | *c* | 11 | 12 | 12 | 18 | 28 | 19 | 25 | 25 | 28 | 30 | 1.57 |
| Ni* | *a* | 31 | 33 | 32 | 37 | 54 | 50 | 34 | 43 | 49 | 58 | 2.21 |
| | *b* | 19 | 22 | 20 | 28 | 44 | 40 | 29 | 37 | 41 | 48 | 2.81 |
| | *c* | 127 | 134 | 130 | 146 | 162 | 154 | 149 | 151 | 157 | 167 | 6.72 |
| Cu* | *a* | 67 | 68 | 68 | 73 | 78 | 79 | 68 | 71 | 75 | 78 | 3.21 |
| | *b* | 13 | 26 | 24 | 29 | 44 | 45 | 31 | 36 | 40 | 47 | 0.62 |
| | *c* | 109 | 111 | 112 | 117 | 128 | 120 | 111 | 116 | 119 | 122 | 6.02 |
| Rb* | *a* | 76 | 79 | 78 | 81 | 89 | 87 | 77 | 83 | 84 | 90 | 3.81 |
| | *b* | 68 | 82 | 72 | 79 | 85 | 85 | 76 | 79 | 80 | 87 | 2.91 |
| | *c* | 43 | 44 | 44 | 47 | 49 | 50 | 44 | 48 | 49 | 52 | 2.15 |
| Y* | *a* | 31 | 33 | 32 | 39 | 44 | 40 | 37 | 39 | 40 | 46 | 1.37 |
| | *b* | 27 | 28 | 27 | 33 | 37 | 39 | 29 | 31 | 35 | 37 | 1.12 |
| | *c* | 23 | 25 | 25 | 27 | 30 | 31 | 26 | 29 | 30 | 31 | 0.91 |
| Mo* | *a* | 34 | 37 | 36 | 38 | 45 | 41 | 37 | 38 | 42 | 40 | 1.53 |
| | *b* | 28 | 32 | 30 | 32 | 41 | 38 | 32 | 35 | 31 | 34 | 1.11 |
| | *c* | 12 | 14 | 14 | 17 | 28 | 23 | 15 | 18 | 20 | 24 | 0.78 |
| Pb* | *a* | 82 | 84 | 85 | 90 | 98 | 97 | 90 | 88 | 93 | 90 | 4.67 |
| | *b* | 65 | 70 | 67 | 75 | 84 | 79 | 71 | 74 | 81 | 79 | 2.38 |
| | *c* | 74 | 78 | 76 | 81 | 99 | 86 | 91 | 89 | 95 | 80 | 2.75 |

**Note:** $\%\cdot10^{-6}$.

Repeated application of SS in willow plantations according to the research scheme led to a significant increase in the content of Fe, Zn, Nb, As, Ni, Cu, Y, Mo, Pb in the aluvisol compared to the control and application of mineral fertilizers. The increase in Ni content in the soil was significant only compared to the control variant.

A comparison of the indicators of the content of chemical elements in the soil under the influence of SS and its composts with other organic materials (options 6 – 10) indicates a significant increase in the content of As, Mo and Pb. No such clear trend was established for other elements.

Under the influence of changes in the content of elements in the soil, the indicators of their content in the roots and above-ground shoots of the energy willow changed significantly. The accumulation of heavy metals in plants was not linear compared to the increase in their concentration in the aluvisol environment under the influence of the use of SS. The highest rates of SS (options 4 – 5), where 60 – 80 t/ha of SS were applied, led to a reliable and significant increase in the content of As, Mo, Pb compared to other research options [Lopushnyak V., Hrytsulyak G., 2014; Lopushniak V., Gritsulyak G., Yakubovsky T. et al., 2020]. The content of Fe, Zn, Sr, Y in these options was at the level of option 10, where compost was applied (SS + straw (3:1) + cement dust 10%) – 40 t/ha. In this version, the indicators of the Nb content. Ni, Cu significantly outweighed the indicators of other options.

The content of Zn, Cu, Mo, Pb in the shoots was the highest in the variant with the highest dose of SS – 80t/ha (option 5). For other elements, a clear dependence of the content on the application doses of SS has not been established.

Calculation of the coefficient of biological absorption [Lopushnyak V., Hrytsulyak G., 2014; Lopushnyak V., Hrytsulyak, H., Voloshin, Y. et al., 2022] provides a more complete picture of the features of the accumulation of chemical elements in plants (Figure 1).

Calculation of bioaccumulation coefficients indicates differential contamination of plant material with heavy metals. Depending on the forms and doses of SS application, the coefficients of biological absorption of chemical elements by energy willow plants varied in a wide range of values (in descending order) for Nb, Mo, Fe, Sr, Pb, As. These indicators for Rb, Y, Cu, Ni varied within 11–22% of the minimum value. For Zn, the value of the coefficient varied slightly between 1.04 and 1.08, and its highest values were recorded in the options where the highest dose of SS 80 t/ha (option 5) and compost (SS + straw (3:1) + cement dust 10%) – 40 t/ha. The highest values of the biological absorption coefficient of Fe, Sr, Nb, As and Pb were also recorded in these options.

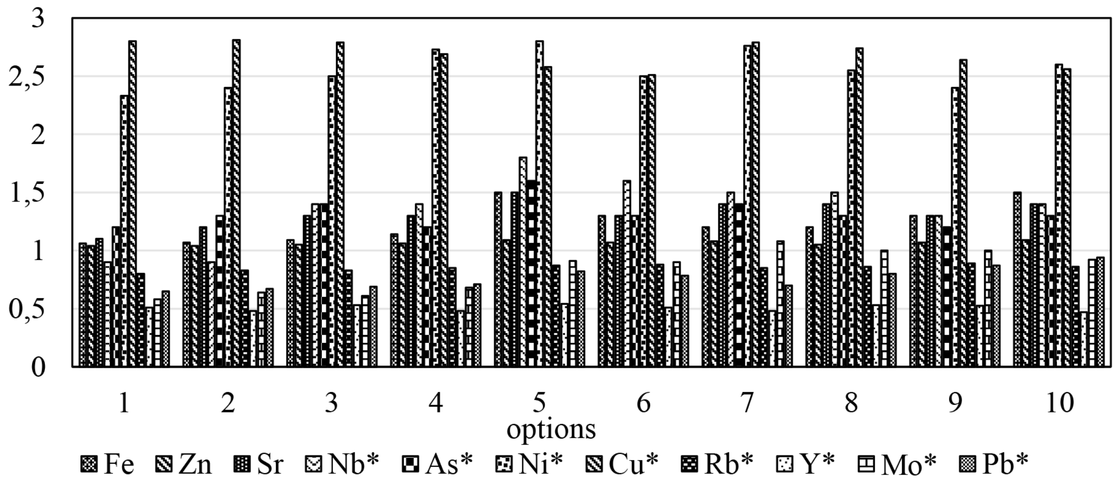


**Figure 1.** Change in the coefficients of biological absorption of chemical elements during repeated application of SS under energy willow, average for 2016–2021

**Table 2.**The influence of the application of SS on the change in the value of the Index of intra-tissue contamination ($I_{itp}$) of energy willow plants by some chemical elements, average for 2016–2021

| Element | Options | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Fe | 1.1 | 1.3 | 1.4 | 2.5 | 1.8 | 2.1 | 1.6 | 1.8 | 2.4 |
| Zn | 1.1 | 1.1 | 1.2 | 2.3 | 2 | 1.7 | 1.6 | 1.6 | 1.8 |
| Sr | 1.9 | 2.0 | 2.1 | 2.7 | 2.4 | 2.1 | 2.3 | 2.5 | 3.1 |
| Nb* | 2.4 | 2.4 | 2.6 | 2.8 | 2.5 | 2.6 | 2.3 | 2.4 | 2.6 |
| As* | 1.5 | 1.5 | 2.2 | 3.7 | 2.3 | 3.1 | 3.1 | 3.5 | 3.5 |
| Ni* | 1.0 | 1.0 | 1.0 | 1.2 | 1.3 | 1.0 | 1.1 | 1.1 | 1.2 |
| Cu* | 1.0 | 1.0 | 1.0 | 1.1 | 1.0 | 1.0 | 1.1 | 1.0 | 1.1 |
| Rb* | 1.0 | 1.0 | 1.0 | 1.2 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 |
| Y* | 1.0 | 1.0 | 1.2 | 1.5 | 1.2 | 1.1 | 1.3 | 1.3 | 1.4 |
| Mo* | 1.1 | 1.2 | 1.3 | 2.0 | 1.8 | 2.0 | 1.9 | 2.1 | 1.8 |
| Pb* | 1.1 | 1.1 | 1.2 | 1.6 | 1.4 | 1.2 | 1.3 | 1.5 | 1.5 |

The use of SS contributed to an increase in the degree of biological assimilation of all investigated chemical elements compared to the application of only mineral fertilizers and composts, except for Cu. Option 10, where 40 t/ha of SS compost with straw, as well as cement dust was applied, had the highest rate of biological absorption of Nb, Y. An increase in the index ($Cba$) of individual elements in the variants with the use of SS (Fe, Sr, Nb, As, Mo, Pb) contributed to the increase of $I_{itp}$ by heavy metals (formula 2) in relation to the variant where only chemical fertilizers were applied (option 2) (Table 2).

The highest indicators of the $I_{itp}$ of energy willow plants with the overwhelming majority of elements (Fe, Zn, Nb, As, Ni, Rb, Y, Mo, Pb), except for Sr and Ni, were established in option 5, where the highest dose of SS was applied in the experiment. In the version where compost was applied (SS + straw (3:1) + cement dust 10%) – 40 t/ha, the highest index of intra-tissue pollution was noted – 3, which prevailed the smallest indicator by 1.5 times.

To find out the trends in the intensity of intra-tissue contamination of energy willow plants, the translocation coefficients ($C_t$) of heavy metals were determined (formula 3), which indicates the ratio of their content in the plant part to the mobile form in the soil [Lopushnyak V., Hrytsulyak G., 2014; Lopushniak V., Gritsulyak G., Yakubovsky T. et al., 2020]. (Figure 2).

First of all, it should be noted that the control variant (without fertilization) had the lowest rates of Fe, Sr, Nb, As, Cu, Rb, Y, Mo, Pb translocation. However, in this variant, the highest indicators of the Zn, Ni translocation coefficient were noted. The coefficient of Cu translocation in the control option without fertilizers was the lowest – 3, but the introduction of even the highest doses of SS (option 5) led to an increase in this indicator only to 3.2, and in all options where fertilizers were applied, the translocation coefficient was 3.1 – 3.2. That is, the introduction of significant doses of SS has a negligible effect on the intensity of Cu accumulation in energy willow plants.

The translocation coefficients of various metals changed unequally under the influence of the use of fertilizers from SS. For example, the Y, Mo translocation coefficient increased by 42–46% compared to the control variant (without fertilizers), for Sr, Ni – by 33%, for Fe, As, Nb, Pb – by 22–29%, for the rest of the metals – by 7 – 18%.

Application of the highest dose of SS in the experiment – 80 t/ha (option 5) caused the highest translocation coefficients of Fe, Nb, Rb, Y, Mo. And the highest values of Sr, As, Pb translocation coefficients were noted in option 10, where compost was applied (SS + straw (3:1) + cement dust 10%) – 40 t/ha, which indicates a significant influx of cement dust into the accumulation of these dangerous metals in plants.

For a generalized assessment of the level of accumulation of heavy metals in various organs of energy willow plants, the Integral indicator of pollution ($IS$) was calculated according to formula 4 (Figure 3).

Determination of the Integral indicator of plant contamination of energy willow was carried out in comparison with the control option, where fertilizers were not applied. It should be noted that the highest levels of pollution were recorded in the variants where fresh SS was applied at the

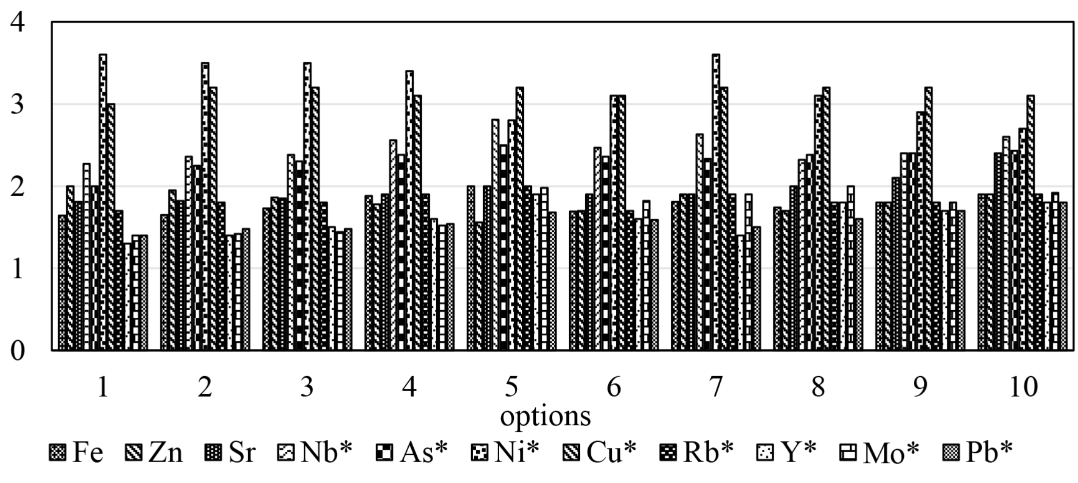


**Figure 2**. The change in the metal translocation coefficient in energy willow depending on the application of SS, the average for 2016-2021

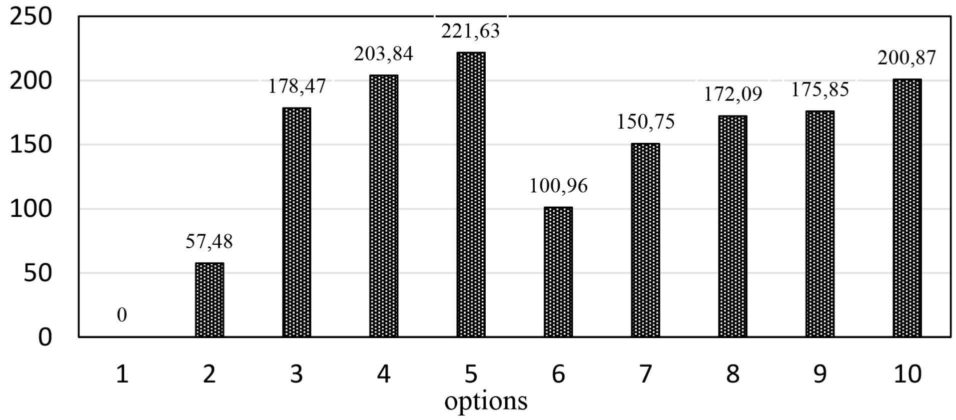


**Figure 3**. Change of the Integral indicator of the pollution of the energy willow plant cover due to the repeated introduction of sewage sludge (2016–2021)

rate of 40 – 80 t/ha. In these options (options 3 – 5), the pollution rate increased almost directly proportional to the applied fertilizers. The application of SScomposts with straw and sawdust led to a significant reduction in the level of pollution. However, in option 10, where compost of SS and straw was applied at the rate of 40 t/ha and additionally cement dust, the pollution of the plant cover reached the indicator of the option, where fresh SS was applied at the rate of 60 t/ha.

For options 2, 3, 4 and 5, linear multiple regression equations, can have the following form:

$$y = 52.546x - 0.428 \quad (5)$$

where: $x$ – the norm of introducing SS in the experiment, t/ha;
$y$ – Integral indicator of pollution of energy willow plants.

The multiple coefficients of determination is $R^2 = 0.8573$, which indicates (according to the Chaddock scale) the high closeness of the dependence of the Integral indicator of pollution on the rate of introduction of SS.

For certain options, where fertilization was carried out with mineral fertilizers in the amount of $N_{100}P_{100}K_{100}$ and composts based on SS, straw and sawdust were applied and with a compensatory dose of mineral fertilizers according to the scheme (options 2, 6, 7, 8, 9 and 10), linear multiple regression equations were calculated dependence of the IS increasing doses of SS, which can have the following form:

$$y = 26.859x + 25.773 \quad (6)$$

where: $x$ – the norm of introducing SS in the experiment, t/ha;
$y$ – Integral indicator of pollution of energy willow plants.

The assessment of the closeness of the relationship between the Integral indicator of vegetation cover pollution and increasing doses of SS composts and sawdust (straw) indicates a very high, almost functional closeness ($R^2 = 0.9545$) of this dependence according to the Chaddock scale.

## CONCLUSIONS

The solution to the problem of safe disposal of municipal solid waste is considered in many countries of the world due to the possibility of its use as a fertilizer in mineral nutrition systems of technical and, especially, energy crops due to its high content of biogenic substances, in particular nitrogen and phosphorus compounds, as well as carbon. However, this method of use may be associated with environmental risks of soil contamination with heavy metals and other pollutants.

Under the influence of the introduction of SS, the indicators of the content of heavy metals in the roots and above-ground shoots of energy willow changed significantly. The highest doses of SS of 60-80 t/ha led to a significant increase in the content of As, Mo, and Pb compared to other research options. The content of Fe, Zn, Sr, Y in these variants was at the level of the variant where compost was applied (SS + straw (3:1) + cement dust 10%) – 40 t/ha. Also, in this version, indicators of Nb content. Ni, Cu significantly outweighed the indicators of other options.

The content of Zn, Cu, Mo, Pb in the shoots was the highest in the variant with the highest dose of SS – 80 t/ha (variant 5). For other elements, a clear dependence of the content on the application doses of SS has not been established. The highest rate of 80 t/ha of SS led to a significant increase in the content of As, Mo, and Pb in plants compared to other research options. The content of Fe, Zn, Sr, Y in this version was at the level of the version where compost was applied (SS + straw (3:1) + cement dust 10%) – 40 t/ha.

The highest value of the Integral index of energy willow plant pollution – 222 was recorded in the variant where fresh SS was applied at the rate of 80 t/ha, which was 17–20 points higher than the values of the closest options of the experiment.

Further scientific studies on the assessment of pollution of sod-podzolic soil during repeated cycles (up to 5 – 7cycles) of the use of agrophytocenoses of energy willow and periodic introduction of SS under this culture relate to the study of the transformation and immobilization of polluting compounds in the soil environment, the influence of changes in the content of organic matter on such transformation processes soil, clarifying the role of physicochemical properties of soil on the bioavailability of heavy metals and the intensity of their assimilation by the root systems of plants, as well as the regularities of their translocation in vegetative organs.

## REFERENCES

1. Bolesta W., Głodniok M., Styszko K. (2022). From sewage sludge to the soil – transfer of pharmaceuticals: A review. International Journal of Environmental Research and Public Health; 19(16):10246. https://doi.org/10.3390/ijerph191610246.
2. Buta M., Hubeny J., Zieliński W., Harnisz M., Korzeniewska E. (2021). Sewage sludge in agriculture – the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops – a review. Ecotoxicology and Environmental Safety, Volume 214, https://doi.org/10.1016/j.ecoenv.2021.112070.
3. Dhanker R., Chaudhary S., Goyal S., Kumar Garg V. (2021). Influence of urban sewage sludge amendment on agricultural soil parameters.Environmental Technology & Innovation, Volume 23.https://doi.org/10.1016/j.eti.2021.101642.
4. Ding Gao, Xin-yu Li, Hong-tao Liu. (2020). Source, occurrence, migration and potential environmental risk of microplastics in sewage sludge and during sludge amendment to soil. Science of The Total Environment, 2020. Volume 742. https://doi.org/10.1016/j.scitotenv.2020.140355.
5. Eid E.M., Alamri S.A.M., Shaltout K.H., Galal T.M., Ahmed M.T., Brima, E.I., Sewelam N. (2020). A sustainable food security approach: Controlled land application of sewage sludge recirculates nutrients to agricultural soils and enhances crop productivity. Food and Energy Security, 9(2). doi:10.1002/fes3.197
6. Elmi A., Al-Khaldy A., Al-Olayan M. (2020). Sewage sludge land application: Balancing act between agronomic benefits and environmental concerns. Journal of Cleaner Production, Volume 250, https://doi.org/10.1016/j.jclepro.2019.119512.
7. Golui, D., Datta, S.P., Dwivedi, B.S., Meena, M.C., Varghese, E., Sanyal, S.K., Trivedi, V.K. (2019). Assessing soil degradation in relation to metal pollution – a multivariate approach. Soil and Sediment Contamination: An International Journal, 28(7), 630–649. doi:10.1080/15320383.2019.1640660
8. Hoang, S.A., Bolan, N., Madhubashani, A.M.P., Vithanage, M., Perera, V., Wijesekara, H., Siddique, K.H.M. (2022). Treatment processes to eliminate potential environmental hazards and restore agronomic value of sewage sludge: A review. Environmental Pollution, 293, 118564. doi:10.1016/j.envpol.2021.118564
9. Hryshko V. M., Piskova O. M. (2014). Osoblyvosti akumulyatsiyi vazhkykh metaliv u lystkakh derevnykh roslyn pry aerohennomu zabrudnenni ekotopiv. Introduktsiya roslyn. № 1(61). S. 93–100.
10. KalenskaS., NovytskaN., StolyarchukT., KalenskyiV., GarbarL., SadkoM., ShutiyO., SonkoR. (2021). Nanopreparations in technologies of plant growing. Agronomyresearch.19(1). https://doi.org/10.15159/AR.21.017.
11. Kirchmann H., Börjesson G., Kätterer T. et al. (2017). From agricultural use of sewage sludge to nutrient extraction: A soil science outlook. Ambio 46, 143–154. https://doi.org/10.1007/s13280-016-0816-3
12. Korsun, S.H., Klymenko, I.I., Bolokhovs′ka, V.A., Bolokhovs′kyy, V.V. (2019). Influence of liming and biological preparations on the translocation of heavy metals in the soil-plant system for polluting ecotops of lead, cadmium, zinc. Agroecological journal, (1), 29–35. doi:10.33730/2077-4893.1.2019.163245.
13. Kumar, V., Chopra, A. K., & Kumar, A. (2017). A review on sewage sludge (biosolids) a resource for sustainable agriculture. Archives of Agriculture and Environmental Science, 2(4), 340–347. doi:10.26832/24566632.2017.020417
14. Lamastra, L., Suciu, N. A., &Trevisan, M. (2018). Sewage sludge for sustainable agriculture: contaminants' contents and potential use as fertilizer. Chemical and Biological Technologies in Agriculture, 5(1). doi:10.1186/s40538-018-0122-3
15. Latosińska J, Kowalik R, Gawdzik J. Risk (2021). Assessment of Soil Contamination with Heavy Metals

from municipal sewage sludge. Applied Sciences.11(2):548. https://doi.org/10.3390/app11020548

16. Lopushniak V., Gritsulyak G., Yakubovsky T., Barchak B., Savyuk R. (2020). Formation of energy willow productivity with re-introduction of sewerage. Ukrainian Black sea Region agrarian science. Vol. 2. p. 63–70.doi: 10.31521/2313-092X/2020-2(106)-7
17. Lopushniak, V., Hrytsuliak, H., Gamayunova, V.,Kozan N., Zakharchenko E., Voloshin Y., Lopushniak H., Polutrenko, M., Kotsyubynska, Y. (2022). A dynamics of macro elements content in eutric podzoluvisols for separation of wastewater under Jerusalem Artichokes. Journal of Ecological Engineering, 2022, 23(4), pp. 33–42. doi: https://doi.org/10.12911/22998993/146268
18. Lopushnyak V., Hrytsulyak G. (2014). Productivity formation model of Osier (Salix viminalis) agrocenosis. Motrol. Lublin – Rzeszow. Vol. 16. № 4. P. 77–81
19. Lopushnyak, V., Hrytsulyak, H., Voloshin, Y., Lopushniak, H., Baran, B. (2022). Bioaccumulation and translocation of heavy metals in plants artichoke during sewage sediment in podzols soils. Ecological Engineering & Environmental Technology, 23(6), 178–187. doi:10.12912/27197050/152919
20. Luczkiewicz A. (2006). Soil and groundwater contamination as a result of sewage sludge land application. Polish J. of Environ. Vol. 15, No. 6. P. 869–876. 21.
21. Markowicz A., Bondarczuk K., Wiekiera A. et al. (2021). Is sewage sludge a valuable fertilizer? A soil microbiome and resistome study under field conditions. J Soils Sediments 21, 2882–2895. https://doi.org/10.1007/s11368-021-02984-122.
22. Mosquera-LosadaR., Amador-García A., Muñóz-Ferreiro N., Santiago-Freijanes J., Ferreiro-Domínguez N., Romero-Franco R., Rigueiro-Rodríguez A. (2017). Sustainable use of sewage sludge in acid soils within a circular economy perspective, CATENA, Volume 149, Part 1. P. 341–348. https://doi.org/10.1016/j.catena.2016.10.007.
23. Nunes N., Ragonezi C., Gouveia C., Pinheiro de Carvalho M. (2021). Review of sewage sludge as a soil amendment in relation to current international guidelines: A heavy metal perspective. Sustainability. 13, 2317. https://doi.org/10.3390/su13042317
24. Panasiewicz, K., Niewiadomska, A., Sulewska, H., Wolna-Maruwka, A., Borowiak, K., Budka, A., Ratajczak, K. (2019). The effect of sewage sludge and BAF inoculant on plant condition and yield as well as biochemical and microbial activity of soil in willow (Salix viminalisL.) culture as an energy crop. PeerJ, 7, e6434. doi:10.7717/peerj.6434
25. PöykiöR., Watkins G., Dahl O. (2019). Characterization of municipal sewage sludge as a soil improver and a fertilizer product. ECOL. CHEM. ENG. S. 26(3):547–557. DOI: 10.1515/eces-2019-0040
26. Pulkrabová, J., Černý, J., Száková, J., Švarcová, A.,Gramblička, T., Hajšlová, J., Tlustoš, P. (2019). Is the long-term application of sewage sludge turning soil into a sink for organic pollutants?: evidence from field studies in the Czech Republic. Journal of Soils and Sediments, 19(5), 2445–2458. doi:10.1007/s11368-019-02265-y
27. Rivier, P.-A., Havranek, I., Coutris, C., Norli, H. R., &Joner, E. J. (2019). Transfer of organic pollutants from sewage sludge to earthworms and barley under field conditions. Chemosphere, 222, 954–960. doi:10.1016/j.chemosphere.2019.02.010
28. Ronald C. Sims, Sean K. Bedingfield, Reese Thompson, Judith L. Sims. Bioenergy from wastewater-based biomass. AIMS Bioengineering, 2016, 3(1): 103-124. doi: 10.3934/bioeng.2016.1.103
29. Rorat A., Courtois P., Vandenbulcke F., Lemiere S. (2019). Sanitary and environmental aspects of sewage sludge management. Industrial and Municipal Sludge, Butterworth-Heinemann, P. 155-180, https://doi.org/10.1016/B978-0-12-815907-1.00008-8.
30. Rybalova O.V., Korobkina K.M. (2017) Novyi pidkhid do otsinky zabrudnennia hruntiv vazhkymy metalamy. Topical Problems of Modern Science. Vol. 5. S. 86–89.
31. Rybalova O., Bryhada O., Sarapina M. (2020). Suchasni metody intehral′noyiotsinky zabrudnennya gruntiv khimichnymy rechovynamy. Dynamics of the development of world science: The 8-th International scientific and practical conference (April 15–17, 2020). Vancouver, Canada. S. 764–771.
32. Sas, E., Hennequin, L.M., Frémont, A., Jerbi, A., Legault, N., Lamontagne, J., Pitre, F.E. (2021). Biorefinery potential of sustainable municipal wastewater treatment using fast-growing willow. Science of The Total Environment, 792, 148146. doi:10.1016/j.scitotenv.2021.148146.
33. Sims, R., K. Bedingfield, S., Thompson, R., & L. Sims, J. (2016). Bioenergy from wastewater-based biomass. AIMS Bioengineering, 3(1), 103–124. doi:10.3934/bioeng.2016.1.103
34. Skowrońska M., Bielińska E., Szymański K., Futa B., Antonkiewicz J., Kołodziej B. (2020). An integrated assessment of the long-term impact of municipal sewage sludge on the chemical and biological properties of soil, CATENA, Volume 189, https://doi.org/10.1016/j.catena.2020.104484
35. SkrylnykYe.V. MaksymenkoN. V., RyzhkovaYa. S., CherkashynaN. I., DobronosP. A. (2020). Agro-environmental rationale of sewage sludge processing and application. Man and Environment. Issues of Neoecology. (33). https://doi.org/10.26565/1992-4224-2020-33-12
36. Stachowicz, F., Trzepiecińsk, T., Wójcik, M., Masłoń, A., Niemiec, W., & Piech, A. (2016).

Agricultural utilisation of municipal sludge in willow plantation. E3S Web of Conferences, 10, 00088. doi:10.1051/e3sconf/20161000088

37. Tsvetkov, I., Tzvetkova, N., & Marinova, S. (2021). Effect of wastewater sludge treatment on early growth and physiological responses of willow (Salix spp.) and poplar (Populus spp.) pot-grown plants. Silva Balcanica, 22(1), 57–65. doi:10.3897/silvabalcanica.22.e58528
38. Wójcik, M., & Stachowicz, F. (2018). The application of biomass ashes in sewage sludge management – a SWOT analysis. E3S Web of Conferences, 44, 00196. doi:10.1051/e3sconf/20184400196
39. Wolna-Maruwka, A., Sulewska, H., Niewiadomska, A., Panasiewicz, K., Borowiak, K., & Ratajczak, K. (2018). The influence of sewage sludge and a consortium of aerobic microorganisms added to the soil under a willow plantation on the biological indicators of transformation of organic nitrogen compounds. Polish Journal of Environmental Studies, 27(1), 403–412. doi:10.15244/pjoes/74184
40. Wydro U., Jabłońska-Trypuć A., Hawrylik E., Butarewicz A., Rodziewicz J., Janczukowicz W., Wołejko E. (2021). Heavy metals behavior in soil/plant system after sewage sludge application. Energies. 14(6):1584. https://doi.org/10.3390/en14061584