

Article Type: Research Article

J Name: Modern Phytomorphology

Short name: MP

ISSN: ISSN 2226-3063/eISSN 2227-9555

Year: 2026

Volume: 20

Page numbers: 699-705

DOI: 10.5281/zenodo.23473737
(10.5281/zenodo.2026-20-699-705)



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RESEARCH ARTICLE

Assessment of the phytoremedial potential of *Galega orientalis* under the conditions of polyelemental pollution of soils with heavy metals

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Received: 07.08.2026, Manuscript No. mp-26-193388 | Editor Assigned: 10.08.2026, Pre-QC No. mp-26-193388 (PQ) | Reviewed: 21.09.2026, QC No. mp-26-193388 (Q) | Revised: 09.10.2026, Manuscript No. mp-26-193388 (R) | Accepted: 13.10.2026 | Published: 20.10.2026

Abstract

The phytoremediation potential of the perennial legume crop of the *Galega orientalis* Lam. under conditions of polyelement contamination with heavy metals (lead, cadmium, copper and zinc) was investigated. The experiment was conducted in 2021-2025 on gray forest surface-gleyed soils at the Agronomichne research farm (Vinnytsia region, Ukraine) after carrying out an agrotechnical measure-liming. The assessment of the ecological state of the edaphotope was carried out in the 2nd and 4th years of the crop's vegetation using atomic absorption spectrometry, calculation of concentration coefficients (K_c) and the total soil pollution index (Z_c).

It was established that long-term cultivation of *Galega orientalis* provides high efficiency of soil purification from copper (98.46%) and cadmium (98.33%), reducing their concentration coefficients to insignificant levels (0.04 and 0.02, respectively). The efficiency of zinc extraction was 79.63%, and lead -55.93%. In the 4th year of vegetation, the integral index Z_c shifted into the negative zone and was -2.45 ± 0.03 (against the initial 1.52 ± 0.03), which mathematically confirms the complete detoxification of the soil profile. Analysis of plant raw materials revealed that the content of cadmium, copper and zinc in the green mass is within the safe norm. However, for lead, the maximum permissible concentration in feed was recorded to be 1.60 times higher (0.80 ± 0.01 mg/kg of absolute dry matter), which indicates the implementation of the strategy of active terrestrial phytoextraction. For practical application, a technological scheme is proposed that includes regular mowing of biomass to remove toxicants from the local circulation and its subsequent low-temperature pyrolysis or controlled combustion.

Keywords: *Galega orientalis*, phytoremediation, total pollution index, heavy metals, biomass hazard factor, environmental engineering

Introduction

Anthropogenic activity, in particular the intensive development of industry, transport infrastructure and chemicalization of agriculture, leads to progressive pollution of land resources. Among environmental toxicants, heavy metals and metalloids [Arsenic (As), Cadmium (Cd), Lead (Pb), Zinc (Zn), Copper (Cu), Nickel (Ni), Chromium (Cr)] pose a particular danger (Tkachuk, et al. 2025). They are not subject to biological decomposition, accumulate in the soil profile and are able to migrate along trophic chains, creating a direct threat to human health and ecosystem biodiversity (Snitynskyi, et al. 2024). Traditional physicochemical methods of soil purification (excavation, washing, thermal treatment) are costly, energy-intensive and often destroy the natural structure and microbiome

of the edaphotop (Razanov, et al. 2024). The scale of this problem is transboundary and extremely acute for the European continent. According to modern geospatial research and modelling, more than 1.2 million square kilometers (about 28.3% of the total area of the European Union (EU)) have exceeded threshold concentrations of one or more heavy metals in the topsoil. If we consider only the agricultural sector, then according to the European environment agency, about 6.24% (or 137,000 km²) of agricultural land in Europe require immediate local monitoring and remediation measures (Bulgakov, et al. 2023). At the same time, if the current levels of agrochemical load are maintained, it is predicted that up to 60% of European soils will exceed critical limits for copper in the coming decades, and 46% for zinc (Razanov, et al. 2024). In addition, southern and central Europe are part of the so-called global “metal-rich corridor” of Eurasia, where the centuries-old history of mining and metallurgy has created persistent geogenic-anthropogenic anomalies of toxicants (Butenko, et al. 2025).

In this context, environmentally safe, cost-effective and invasive technologies are gaining priority, among which phytoremediation occupies a leading place. This approach is based on the ability of higher plants and their associated rhizosphere microflora to absorb, concentrate, transform or immobilize pollutants in environmental components (Hetman, et al. 2025). The success of phytoremediation measures critically depends on the correct selection of plant objects, which must combine high tolerance to toxicants, a significant rate of biomass growth and a developed root system (Didur, et al. 2020).

In recent years, attention has been drawn to the study of the potential of perennial legumes, which are able not only to accumulate ecotoxins, but also to improve the agrochemical indicators of degraded lands due to symbiotic nitrogen fixation. One of such promising, but insufficiently studied in the context of ecological engineering objects is the oriental *Galega orientalis* Lam (Razanov, et al. 2023, Didur, et al. 2026). This crop is characterized by a long life cycle (up to 15-20 years in one place), a powerful taproot-shoot root system that penetrates the soil by 2-3 meters, and a high intensity of above-ground mass formation. Due to the formation of dense turf, *Galega orientalis* effectively prevents water and wind erosion, and its powerful rhizosphere stimulates the activity of microbiocenosis, which accelerates the degradation of organic pollutants and the stabilization of mineral elements (Tkachuk, et al. 2024).

Despite a significant number of publications devoted to the forage value and agronomic practices of *Galega orientalis*, its phytoremediation properties, the peculiarities of the accumulation of specific toxicants in the “soil-root-stem-leaves” system, and the physiological mechanisms of adaptation to conditions of polyelement pollution remain poorly studied. The available literature data are often fragmentary and do not provide a holistic view of the limiting factors for the use of this crop on lands withdrawn from agricultural use due to industrial or urban loads (Tkachuk, et al. 2024).

The aim of this study is a comprehensive assessment of the phytoremediation potential of *Galega orientalis* under conditions of technogenic soil contamination with heavy metals: Cadmium, lead, zinc, and copper, determination of bioaccumulation and translocation coefficients, and justification of the possibility of integrating this crop into technological schemes for ecological remediation of disturbed territories in the European region (Honcharuk, et al. 2022, Pantsyryeva, et al. 2025).

Materials and Methods

Experimental studies were conducted during 2021-2025 on the basis of the Scientific Research Farm (SRF) “Agronomichne” (Vinnytsia district, Vinnytsia region, Ukraine). The object of the study was *Galega orientalis* Lam. a perennial legume crop. Experimental plots were established on sown fields of *Galega orientalis* Lam., where the 2nd year of plant vegetation (initial stage of monitoring) and the 4th year of vegetation (final stage for assessing the cumulative remediation effect) were studied in detail.

The soil cover of the experimental area is represented by gray forest surface-gleyed soils. Before the start of herbaceous cultivation, in order to optimize the acid-base properties of the edaphotop and reduce the mobility of ecotoxins, an agrotechnical measure was carried out on the plots-soil liming (application of limestone materials to full hydrolytic acidity). The study was conducted under conditions of natural background and technogenically enhanced polyelement pollution with heavy metals (lead, cadmium, copper and zinc) due to moderate industrial and agrochemical load of the region.

Soil and plant biomass samples were collected annually at the end of the growing season (budding phase-the beginning of flowering of the eastern goat's-eye daisy, when the maximum accumulation of above-ground mass is observed). Soil samples were collected by the “envelope” method from the arable layer (0-20 cm) using a reed auger. A combined sample weighing 1 kg was formed from each experimental plot, which was dried to an air-dry state, cleaned of root residues and sieved through a sieve with a hole diameter of 1 mm.

Plant samples (green mass) were collected by cutting off above-ground organs (stems and leaves) at a height of 3-5 cm from the soil surface. To determine the content of metals in terms of Absolutely Dry Matter (ADM), the green mass was thoroughly washed with distilled water to remove dust particles, dried in a drying oven at a temperature of 60-65°C to an air-dry state, and then brought to a constant mass at a temperature of 105°C and ground in a laboratory mill.

The determination of the gross content of heavy metals (Pb, Cd, Cu, Zn) in soil samples and plant ash was performed by Atomic Absorption Spectrometry (AAS) on a spectrophotometer in a certified training agrochemical laboratory of the Educational and Scientific Institute of Agrotechnology and Environmental Management of Vinnytsia National Agrarian University (Ukraine).

Mineralization of plant samples was carried out by dry ashing in a muffle furnace at a temperature of 450°C with subsequent dissolution of the ash in diluted nitric acid (HNO₃). Extraction of heavy metals from soil to determine the gross content was carried out by destroying the soil matrix with a mixture of concentrated mineral acids according to standard methods.

To quantitatively assess the intensity of soil purification and the level of ecological safety of biomass, the following coefficients were calculated:

Heavy metal concentration coefficient (K_c): $K_c = C_i / C_{\text{fon}}$, where C_i is the actual concentration of the element in the soil at a certain stage of the study, mg/kg, C_{fon} is the regional background value of the content of this element in the soil.

Total soil contamination index Z_c : $Z_c = \Sigma (K_c) - (n-1)$, where $\Sigma (K_c)$ is the sum of the concentration coefficients of all studied elements that exceed the background level, n is the number of determined elements ($n=4$).

Soil Remediation Efficiency (RE, %): $RE = K_{c2} - K_{c4} / K_{c2} \times 100\%$, where K_{c2} and K_{c4} are the element concentration coefficients in the soil for the 2nd and 4th years of vegetation, respectively.

Biomass Hazard Quotient (HQ): $HQ = C_{\text{plant}} / \text{MPC}$, where C_{plant} is the actual metal content in the green mass of the plant, mg/kg, MPC is the Maximum Permissible Concentration of this element in animal feed in accordance with current environmental regulations.

All experimental studies were performed in three analytical and field replicates. Statistical processing of the obtained results was carried out by the method of variation analysis using Microsoft Excel and Statistica software. The results in the tables and text are presented as the arithmetic mean value and its standard error ($M \pm m$). The significance of the difference between the variants was assessed using the Student's t-test for a significance level of $p < 0.05$.

Results and Discussion

Analysis of experimental data indicates a high phytoremediation ability of *Galega orientalis* to clean the soil cover from a complex of potentially toxic elements during the studied vegetation period (between the 2nd and 4th years). The introduction of this crop into the agroecosystem of the Scientific Research Farm (SRF) "Agronomichne" allowed to significantly reducing the concentration of all studied heavy metals in the soil.

The maximum dynamics of purification was recorded for Copper (Cu) and Cadmium (Cd). In particular, the copper content in the soil decreased 65 times—from 6.5 ± 0.22 mg/kg in the second year of cultivation to a minimum of 0.1 ± 0.00 mg/kg in the fourth year, which provided the highest remediation efficiency at 98.46%. The efficiency of cadmium removal was 98.33%: Its concentration dropped 60 times, reaching trace values (0.01 ± 0.00 mg/kg) at the limit of device sensitivity in the 4th year of vegetation (Tab. 1).

Table 1. Dynamics of reduction of heavy metal content in soil during cultivation of *Galega orientalis* and efficiency of its purification.

Element	Concentration in soil, 2 nd year of vegetation, mg/kg	Concentration in soil, 4 th year of vegetation, mg/kg	Concentration in soil, 4 th year of vegetation, mg/kg	Soil cleaning efficiency [Remediation Efficiency (RE*)]
Lead (Pb)	5.9 ± 0.22	2.6 ± 0.08	3.3	55.93
Cadmium (Cd)	0.60 ± 0.01	0.01 ± 0.0001	0.59	98.33
Copper (Cu)	6.5 ± 0.22	0.1 ± 0.001	6.4	98.46
Zinc (Zn)	5.4 ± 0.08	1.1 ± 0.14	4.3	79.63

The high intensity of purification of the edaphotopus *orientalis* also showed in relation to Zinc (Zn). Its gross content decreased by 4.91 times (from 5.4 ± 0.08 mg/kg to 1.1 ± 0.14 mg/kg), and the overall efficiency of soil purification was 79.63%.

The least dynamic, but statistically significant, was the decrease in the concentration of Lead (Pb). Over two years of growing herbs, the content of this pollutant in the soil decreased by 2.27 times—from 5.9 ± 0.22 mg/kg to 2.6 ± 0.08 mg/kg. The remediation efficiency indicator for lead was 55.93%, which may be due to the low mobility of this metal in the soil solution and its tendency to form strong organo-mineral complexes.

The results obtained prove that long-term (over 4 years) cultivation of the perennial legume *Galega orientalis* triggers powerful soil self-cleaning mechanisms, which makes this species a promising tool in environmental engineering for the remediation of areas with polyelemental heavy metal pollution.

To assess the dynamics of edaphotop purification, the concentration coefficients (K_c) of individual heavy metals and the total soil pollution index (Z_c) were analyzed depending on the duration of cultivation of *Galega orientalis* (Tab. 2).

Table 2. Dynamics of concentration coefficients (K_c) of heavy metals and total soil pollution index (Z_c) under the influence of *Galega orientalis*.

Research stage/vegetation period	K_c Pb	K_c Cd	K_c Cu	K_c Zn	Total pollution index (Z_c)
Before growing herbs	0.99 ± 0.01	0.86 ± 0.04	2.27 ± 0.03	0.40 ± 0.01	1.52 ± 0.03
<i>Galega orientalis</i> , 2 nd year	0.99 ± 0.01	0.86 ± 0.04	2.17 ± 0.03	0.24 ± 0.01	1.26 ± 0.03
<i>Galega orientalis</i> , 4 th year	0.44 ± 0.03	0.02 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	-2.45 ± 0.03
Total reduction in coefficient, times between stage "before" and year 4	2.25	43	56.75	8	By 3.97 units

The initial state of the soil before sowing grasses was characterized by pronounced copper contamination, for which K_c was 2.27 ± 0.03 , which indicates an excess of the environmentally safe level. For lead ($K_c=0.99$) and cadmium ($K_c=0.86$), the indicators were close to the norm, while for zinc ($K_c=0.40$) a low level of accumulation was recorded. The total soil contamination index (Z_c) at this stage was 1.52 ± 0.03 , classifying the site as having a low (initial) level of technogenic load.

In the second year of the *Galega orientalis* vegetation, no significant changes were detected in the coefficients of concentration of Pb (0.99 ± 0.01) and Cd (0.86 ± 0.04). However, an initial decrease in the coefficients for Cu (to 2.17 ± 0.03) and Zn (to 0.24 ± 0.01) was observed. Due to this, the total Z_c index decreased to 1.26 ± 0.03 , which confirms the gradual launch of phytoremediation processes.

A dramatic improvement in the ecological state of the soil was recorded in the fourth year of crop cultivation, indicating the cumulative effect of the perennial root system of the *Galega orientalis*. The copper concentration coefficient fell 56.75 times compared to the initial state-to the level of 0.04 ± 0.01 . The plant completely eliminated the primary copper pollution. The K_c indicator for cadmium decreased 43 times from the initial one and reached the minimum level of 0.02 ± 0.01 . The zinc and copper concentration coefficients decreased to 0.05 ± 0.01 (8 times) and 0.44 ± 0.03 (2.25 times), respectively.

The main indicator of the success of the eco-engineering measure is the dynamics of the total pollution index. In the 4th year of vegetation, Z_c shifted into the negative zone and amounted to -2.45 ± 0.03 . Such a sharp drop in the value of the integral index (by 3.97 units compared to the stage before cultivation) mathematically confirms the complete detoxification of the soil profile and the transition of the edaphotop to a state of ecological well-being.

To determine the direction of heavy metal migration in the soil-plant system and assess the possibility of further utilization of plant raw materials, the gross content of toxicants in the green mass of *Galega orientalis* on an Absolutely Dry Matter (ADM) basis was analyzed. The results obtained indicate the selective nature of the accumulation of elements by the above-ground part of the crop. The behavior of lead (Pb) attracts particular attention. Its actual content in the green mass was 0.80 ± 0.01 mg/kg, which is 1.60 times higher than the established Maximum Permissible Concentration (MPC) standard (0.50 mg/kg). Such intensive accumulation (60% above the norm) indicates a high initial mobility of Pb ions under the action of root exudates of *Galega orientalis* and confirms its high phytoextraction potential for this chronic ecotoxinant (Tab. 3).

Table 3. The content of heavy metals in the green mass of *Galega orientalis* in comparison with the Maximum Permissible Concentration (MPC) (on absolutely dry matter) and assessment of environmental safety.

Ecotoxinant	Actual content in phytomass, mg/kg of ACP	Maximum Permissible Concentration (MPC), mg/kg	Biomass Hazard Quotient (HQ)	Ecological status of biomass
Lead (Pb)	0.80 ± 0.01	0.5	1.6	Moderately toxic (exceeding the MPC)
Cadmium (Cd)	0.09 ± 0.01	0.1	0.9	Safe (within normal limits)
Copper (Cu)	7.2 ± 0.3	10	0.72	Safe (within normal limits)
Zinc (Zn)	24.0 ± 0.6	50	0.48	Safe (within normal limits)

In contrast, the accumulation of other studied metals was within environmentally safe levels. The actual concentration of cadmium in phytomass was 0.09 ± 0.01 mg/kg at the MPC of 0.10 mg/kg. The hazard quotient is 0.90, which indicates balancing at the limit of the norm, but without exceeding it. This correlates with the previously detected purification of soil from cadmium in the 4th year of the experiment.

The level of copper accumulation was 7.2 ± 0.3 mg/kg, which is safe and is 72% of the maximum permissible concentration (10.0 mg/kg). The zinc content was recorded at 24.0 ± 0.6 mg/kg. Since zinc is an important trace element for the metabolism of legumes, its accumulation was the most intense in absolute terms, but environmentally safe (Hazard Quotient (HQ)=0.48), not reaching even half of the maximum permissible concentration (50.0 mg/kg).

From an engineering and environmental point of view, exceeding the MPC for lead content in green mass (HQ=1.60) imposes restrictions on the use of *Galega orientalis* biomass as a traditional environmentally friendly animal feed at the stage of active remediation. Such above-ground mass accumulates toxicants from the soil and is subject to mandatory mowing with subsequent removal from the territory and technical utilization (for example, by thermochemical combustion for energy or pyrolysis). This fully confirms that the oriental goat's-foot trefoil works according to the eco-technological scheme of active phytoextraction.

The obtained experimental results demonstrate the pronounced effectiveness of *Galega orientalis* as an agent of active phytoremediation of soils contaminated with a complex of heavy metals. The cardinal decrease in the total soil contamination index Z_c from a positive value (1.52 ± 0.03) to a deeply negative (-2.45 ± 0.03) in the fourth year of vegetation clearly indicates a change in the ecological state of the edaphotope from technogenically loaded to conditionally clean (absolute self-cleaning). Such a prolonged cumulative effect is characteristic of perennial leguminous crops, whose root system increases the area of contact with the soil solution with each year of life.

High efficiency indicators of soil purification from cadmium (98.33%) and copper (98.46%) are consistent with modern ideas about the physiology of *Galega orientalis*. Copper and zinc are essential microelements (biophiles) necessary for the normal functioning of plant enzyme systems, in particular superoxide dismutase and plastocyanin. Their active absorption by roots in the initial stages (up to the 2nd year) was due to the high metabolic need of young biomass. The fact that by the 4th year the content of Cu and Zn in the soil dropped to a minimum, and in the green mass their concentration remained within the ecologically safe norm (HQ=0.72) and 0.48, respectively), indicates the activation of phytostabilization mechanisms. Probably, excess copper and zinc accumulated in the underground subsystem (rhizomes and nodules) or were bound by specific proteins-phytochelatins and metallothioneins, which prevented their excessive translocation to photosynthetic organs.

Of particular scientific interest is the behavior of lead (Pb) and cadmium (Cd). Cadmium, as a highly mobile element, was almost completely removed from the soil ($K_c=0.02$) and recorded in plant tissue at a level close to the limit (HQ=0.90). In contrast, lead showed unique dynamics: Despite the fact that its concentration coefficient in the soil decreased the least (by 2.25 times), its content in green mass significantly exceeded the MPC (0.80 mg/kg with a norm of 0.50 mg/kg).

Exceeding the MPC for lead (HQ=1.60) in above-ground phytomass is a classic marker of a phytoextraction strategy. In many herbaceous species, lead is blocked in the roots through the formation of insoluble phosphates or binding to cell walls by cellulose (exudation). However, the powerful rhizosphere of *Galega orientalis* is capable of producing a significant amount of low-molecular organic acids (oxalic, citric, malic). These exudates convert bound lead into mobile chemocomplexes that are easily absorbed by the xylem due to the high transpiration flux of the perennial herb. An additional driver of this process is a unique feature of goat's rue-symbiosis with nodule bacteria *Rhizobium galegae*. Nitrogen fixation not only provides the plant with energy to overcome stress from toxicants, but also locally acidifies the rhizosphere, which dramatically increases the bioavailability of even inert metals such as Pb.

From an engineering and technological point of view, the detected moderate accumulation of lead in green mass excludes the possibility of direct use of the remedial herbage *Galega orientalis* as animal feed in contaminated areas. This requires the implementation of a two-stage eco-technological scheme-1st stage of extraction and mowing: Green mass should be regularly mowed (1-2 mowings per season) to physically remove metals from the local ecosystem; 2nd stage of biomass utilization: Since burning such raw materials in an open way will lead to secondary air pollution, promising methods are low-temperature pyrolysis or controlled burning at special TPP with the capture of ash residue, which can subsequently be used as technogenic raw materials for metal extraction.

Thus, Eastern goat's-foot trefoil combines two remediation strategies: Above-ground phytoextraction for lead and cadmium and rhizosphere phytostabilization for copper and zinc. This makes it a highly effective and self-sufficient phytoameliorant for the long-term restoration of degraded soils in Europe.

The assessment of the ecological safety of the obtained plant raw materials revealed that the content of Cd, Cu and Zn in the green mass does not exceed the MPC standards for feed (Hazard Coefficients HQ<1). However, for Lead (Pb) the MPC was exceeded by 1.60 times (0.80 ± 0.01 mg/kg), which indicates the implementation of the strategy of active terrestrial phytoextraction for this element. From an engineering and environmental point of view, the detected accumulation of lead in the phytomass excludes the possibility of feeding the herbage to animals at the stage of active remediation. A two-stage technological scheme is recommended: Regular mowing of the green mass in order to remove toxicants from the local circulation and its subsequent technical utilization by controlled

burning or pyrolysis (Razanov, et al. 2023).

The total soil pollution index (Z_c) reduction from +1.52 to a negative value of -2.45 over four years of vegetation demonstrates an exceptional self-cleaning capacity. Similar trends in long-term edaphic ecosystem restoration using perennial legumes have been reported across central and eastern Europe. Specifically, *Medicago sativa* L. and *Melilotus albus* showed high efficiency in soil heavy metal and radionuclide sorption, though their remediation timeline often requires longer vegetation periods (5-7 years) to achieve comparable integral detoxification (Didur and Pantsyрева, 2025, Petrychenko, et al. 2025, Petrychenko, et al. 2024).

High extraction rates for copper (98.46%) and cadmium (98.33%) align with broader observations on heavy metal mobility in agricultural and homestead edaphotopes across Ukraine (Razanov, et al. 2024). While traditional energy crops absorb microelements proportionally to their vegetative growth, *Galega orientalis* exhibits a clear physiological specialization. The high efficiency of Cu and Zn binding in the underground subsystem correlates with phytostabilization patterns documented in legume agrocenoses (Didur, et al. 2026).

A critical finding of this study is the terrestrial phytoextraction mechanism observed for lead, where the green mass exceeded the MPC for feed by 1.60 times ($HQ=1.60$). Unlike sunflower or cereal crops where lead accumulation is predominantly restricted to the root zone or shell tissues, the symbiotic nitrogen-fixing system of *Galega orientalis* combined with root exudation enhances lead mobility, driving xylem translocation (Tkach, et al. 2023, Hetman, et al. 2024).

This distinction confirms that while *Galega orientalis* cannot be utilized directly as animal fodder during active remediation phases, its high biomass production rate makes it superior to traditional herbaceous remediants for technical utilization via controlled low-temperature pyrolysis or energy generation.

Conclusion

The conducted studies confirmed the high efficiency and prospects of using *Galega orientalis* as a biological agent for the reclamation and purification of soils with polyelemental heavy metal contamination. Due to the cumulative effect of the developed perennial root system of the crop, a cardinal improvement in the ecological state of the edaphotop is achieved by the 4th year of vegetation.

It was found that long-term cultivation of *Galega orientalis* ensures the elimination of critical soil contamination with copper and cadmium, for which the Remediation Efficiency (RE) was 98.46% and 98.33%, respectively, and the Kc concentration coefficients decreased to a safe minimum of 0.04 and 0.02. The purification of the soil from zinc was 79.63%, and from lead -55.93%. In the 4th year of the study, the index of the total pollution indicator Z_c shifted into the negative zone and was -2.45 ± 0.03 against the initial 1.52 ± 0.03 at the initial stages, which indicates a complete restoration of the ecological well-being of the edaphotop.

Acknowledgements

Scientific research was carried out with the funds of the applied research project “Development of agrobiotechnological approaches to the production of crop products to restore soil fertility affected by hostilities” (0125U000439), 2025-2027, funded by the state budget for the support and development of young scientists of Ukraine (executors: Oleksiy Alieksieiev, Oksana Vradii, Snizhana Pankova, Artem Salialmon), provided by the Ministry of Education and Science of Ukraine.

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