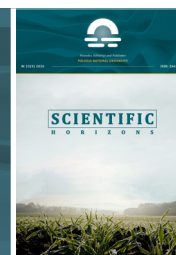


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Background concentrations and remediation strategies for heavy metals in soil ecosystems

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Abstract. The relevance of the present study is related to the growing anthropogenic pressure on Ukraine's land resources. This pressure has been further intensified by the consequences of Russia's full-scale war against Ukraine, which has continued since 2022. The destruction of industrial infrastructure and the extensive use of ammunition became the reasons of the uncontrolled accumulation of toxic elements in the soil profile. The purpose of the study was to systematise and summarise scientific data on the natural content of barium, zirconium, strontium, lead, arsenic, zinc, copper, and nickel in the Earth's crust and soil ecosystems. The study also examined existing strategies for the remediation of contaminated soils. To achieve this aim, a critical analysis and systematisation of scientific literature were carried out within the framework of the research. The study summarised data on regional background concentrations of heavy metals and identified critical determinants, which influence the mobility and bioavailability in the soil-plant system. These factors include pH level, organic matter content and the adsorption capacity of soil. The analysis also revealed gaps in Ukrainian legislation concerning the regulation of several studied metals in agricultural products and animal feed. This points out the need to improve the existing regulatory framework. Given the international experience, several effective hyperaccumulator plants for soil clean-up were defined. These plants encompassed industrial hemp for the phytoextraction of lead and nickel, sunflower and *Cortaderia nitida* for zinc, Indian mustard for barium and nickel, as well as specific aquatic plants such as cattail and papyrus. The findings showed that the use of local wild-growing species adapted to particular ecological niches may provide a basis for highly effective and biologically safe strategies for the reclamation of degraded land. The practical value of the study lies in its justification of phytoremediation as one of the most cost-effective and environmentally neutral methods for restoring damaged areas

Keywords: geochemical background; bioavailability; food security; hyperaccumulators; phytostabilisation; phytoextraction; fertility restoration

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INTRODUCTION

The accumulation of large amounts of pollutants in soils, including heavy metals, became unavoidable (Datsko *et al.*, 2024). It is because of increasing anthropogenic pressure, especially amid Russia's invasion of Ukraine and intensive industrialisation. The problem is particularly acute in regions affected by hostilities. Destruction of industrial facilities, the use of military equipment and the deployment of ammunition lead to the large-scale release of toxic elements into the environment. Once accumulated in the soil profile, these elements alter its physicochemical properties, suppress soil microflora and enter food chains. It is necessary to define the natural geochemical background of metals clearly for an accurate assessment of technogenic pollution and the selection of appropriate clean-up strategies (Lopushniak *et al.*, 2022).

Ukrainian and international researchers widely study the monitoring of soil ecosystem degradation and the determination of background elemental concentrations. O. Tonkha *et al.* (2025) carried out a comprehensive assessment of soil contamination levels in southern Ukrainian regions directly affected by hostilities, focusing on southern low-humus chernozems. The study recorded substantial deviations from environmental standards. In particular, the concentration coefficient for copper ranged from 8.2 to 81.19. In affected areas containing fragments of molten metal, the individual ecological risk for cadmium rose to 1,228, while the total risk index reached 1,805. V. Zatserkovnyi *et al.* (2025) proposed a different approach to solving agrochemical problems through automation. The authors developed an information technology for precision agriculture aimed at improving the monitoring of agricultural land conditions.

International experience in determining the natural content of elements shows considerable variation in regional approaches. According to M.R. Alfaro *et al.* (2015), an assessment of the geochemical background in Cuba found that natural nickel and chromium levels in local soils were substantially higher than global averages. This was linked to the specific composition of parent rocks. The reference soil quality values developed by the authors reached 170 mg/kg for nickel and 153 mg/kg for chromium, indicating pronounced natural geochemical enrichment. Meanwhile, the analysis of fractional composition showed low bioavailability of copper, nickel, chromium, antimony, and arsenic. This reduces the risk of the intensive transfer into plant products. Y. Sun *et al.* (2019), in turn, conducted a systematic review of the evolution of soil quality standards in China and compared these standards with regulatory approaches in the United Kingdom. The authors underlined the importance of background differentiation. The researchers noted that China's first environmental soil quality standards, approved in 1995, applied uniform limit values for eight heavy metals across the entire

country. Such an approach did not reflect geographical heterogeneity, soil type diversity or integrated environmental factors. As a result, individual provinces, including Hunan, later had to develop the pragmatic remediation targets. A major step in the evolution of the regulatory framework came in 2018, when updated standards replaced the previous system. The new framework introduced a two-level assessment model based on environmental screening values and risk intervention values. These modern limits rely on human health risk assessment procedures, vary depending on pH and clearly distinguish between land-use categories, including agricultural land and construction land.

Despite the large amount of experimental data on pollution levels, current scientific literature still lacks an integrated systematisation of methods for differentiating the natural geochemical background and assessing the bioavailability of elements. This gap is especially noticeable for territories exposed to combined military and industrial pressure. The purpose of the present article was to summarise global scientific approaches to establishing reference values for heavy metal content in the Earth's crust and soils. The study also aimed to provide a critical analysis of existing remediation strategies for agroecosystems. Analysis, critical synthesis and systematisation of scientific sources and current regulatory documents underlay the methodology of the present review. The work was performed in several consecutive stages. At the first stage, a targeted search for relevant materials was conducted in leading international and national scientometric databases, including Scopus, Web of Science and Google Scholar. The search used combinations of keywords such as "geochemical background concentrations", "natural metal content in soil", "heavy metal bioavailability", "soil remediation" and "soil and military actions" in Ukrainian and English. Clear source selection criteria were applied to create an objective sample. The analysis comprised only peer-reviewed studies published mainly in 2020-2025. Non-peer-reviewed publications, articles outside the research topic and outdated monitoring data were excluded. The collected information was structured by several thematic areas at the stage of critical analysis and synthesis. These areas encompassed sources of toxicant input, methods for assessing total metal content, biological availability within the "soil-plant" chain, and the ecological and economic effectiveness of physicochemical and biological remediation methods. A separate analytical component of the study was the systematic examination of the provisions of Order of the Ministry of Health of Ukraine No. 368 (2013). The final comparative analysis, which compared international data with national regulatory instruments, made it possible to summarise existing approaches, identify research gaps in the study of poorly investigated element migration and justify optimal strategies for land remediation.

Natural content and comparative geochemical analysis of heavy metals in soil ecosystems

Evaluating changes in the elemental composition of soils under anthropogenic pollution requires a clear distinction between natural elemental fractions and technogenic inputs. P. Madejón (2013) showed that the natural content of barium in the Earth's crust varied considerably, ranging from 425 to 668 mg/kg. In spite of playing no major role in the physiological development of plants, the distribution and accumulation of the above element deserve detailed attention. Barium enters plant organisms mainly from natural sources. This can be explained with the fact that chemical analysis of fertilisers confirmed the absence of high concentrations of this metal in industrial fertilisers.

D.T. Lamb *et al.* (2013) and L.K. Wang *et al.* (2018) described the mechanism of bioaccumulation in detail. In line with findings provided by aforementioned authors, barium was actively absorbed by the root system and then transported to assimilatory organs. However, its translocation was less efficient than the translocation of potassium. Plant residues decomposed. This process formed a specific geochemical cycle after this. This cycle enriched the upper soil horizons. L.K. Choudhary & A. Kumar (2024) reported that the biological effect of barium had a dual, dose-dependent character. It sometimes took part in certain metabolic reactions at very low concentrations. It acted as a dangerous toxicant at elevated levels, especially above 500 mg/kg. It disrupted nutrient uptake, slowed the development of roots and above-ground organs, and induced intense oxidative stress in plant cells. L.K. Choudhary & A. Kumar (2025) confirmed this assumption to the full extent in later research. The effects of barium were clearly differentiated using wheat as an example. The authors proved that low barium doses, up to 10 µg/g, had a promoting effect. Such doses stimulated chlorophyll accumulation and biomass growth. Critical concentrations, from 100 to 1000 µg/g, produced acute toxicity. The above-mentioned concentrations caused a sharp reduction in root length, a decrease in leaf surface area and a fall in overall seed productivity by more than 40%.

Unlike barium, zirconium is relatively more widespread in the lithosphere. Nevertheless, its biological role for phytocoenoses remains minimal. Pursuant to S. Ghosh *et al.* (1992), the average zirconium content in the lithosphere is around 300 mg/kg. Its concentration in soils ranges from 32 to 850 mg/kg. T.A. Hayes and M.E. Kassner (2006), M. Shahid *et al.* (2013), found that zirconium shows low mobility in the natural environment. This is due to its intense adsorption on solid surfaces of the soil absorption complex. The consequence is that the element accumulates mainly in the underground biomass of plants. The scientific debate on zirconium phytotoxicity remained open. A. Hbika *et al.* (2025) recorded a negative effect of zirconium on certain metabolic processes, but these results were

isolated and required further verification. However, the almost complete immobility of zirconium and its resistance to weathering represent its main value in modern geochemical studies. M. Chen *et al.* (2024) demonstrated that zirconium serves as an ideal natural marker, or reference element because of its stability. Comparing the concentrations of mobile toxicants with the content of immobile zirconium enables researchers to calculate soil enrichment factors accurately. This is crucial for environmental monitoring, since it makes it possible to distinguish the natural lithogenic background of soil from artificial anthropogenic pollution, including pollution of military origin. I. Martínez-del-Pozo *et al.* (2026) supported further the unique status of zirconium as a reference element. The authors showed that zirconium demonstrated the highest measurement stability and accuracy among all trace elements during large-scale assessment of geochemical background using portable X-ray fluorescence analysers. This metal is strongly related to parent rock and does not depend on external factors, its spatial distribution acts as a reliable indicator. In field conditions, this marker helps define the natural boundaries of soil layers quickly and separate these layers from areas of artificial technogenic or military contamination.

A comparative analysis of alkaline earth metal distribution indicates the high migration capacity of strontium. In conformity with M.J. Chowdhury & R. Blust (2011), strontium accounts for around 0.037% of the Earth's crust. Its vertical migration rate increased substantially under conditions of higher moisture. The authors pointed out that humic substances in the upper horizons influenced the behaviour of this metal in two ways. On the one hand, these substances stimulated the formation of mobile organomineral complexes. Conversely, the substances bound strontium and prevented its leaching from the soil profile under certain conditions. Artificial application of calcium fertilisers or soil liming is an effective way to reduce strontium toxicity in agroecosystems due to this similarity. Saturating the soil solution with calcium blocks passive strontium uptake by the root system through ion antagonism (Gupta *et al.*, 2017). Modern plant physiology also revealed the ability of strontium to act as an effective protective barrier against other, more dangerous toxicants. J. Liu *et al.* (2023) underscored that the presence of strontium in the environment can substantially reduce the uptake of highly toxic cadmium by the root system. Due to antagonism between these elements, strontium helps plants maintain stable chlorophyll levels, activates intracellular antioxidant defence and reduces biomass growth inhibition in areas contaminated by several elements.

Lead and arsenic pose the highest level of environmental danger and agronomic significance among the analysed elements. Military and industrial emissions exert influence over the background concentrations of these elements. E. Steinnes (2013) and S.M. Mousavi *et*

al. (2022) found that lead exists in soil systems as fractions with different degrees of mobility. The authors stressed that water-soluble anions, including nitrates and acetates, created the greatest threat to agroecosystem stability. These compounds increased lead mobility and raised the risk of its migration into groundwater. H. Cui *et al.* (2024) made a significant contribution to understanding lead dynamics in surface horizons. The authors studied metal mobilisation under conditions of intense atmospheric deposition. The researchers identified a critical scientific contradiction, which implies that new atmospheric inputs of lead are much more dangerous for the environment because 42.0-89.5% of the total lead in atmospheric deposits occurs in bioavailable and mobile forms. The same study experimentally showed that continuous atmospheric input of fresh lead can completely neutralise or substantially weaken the fixing effect of widely used chemical amendments such as lime. Newly deposited metal fractions rapidly increase mobile pools of the element in the upper 0-5 cm layer of the soil profile. Within the framework of the molecular level, the critical danger of lead entering plant tissues lies in the development of severe oxidative stress. N. Kumar & A.K. Jha (2024) noted that lead accumulation in cells induces excessive formation of reactive oxygen species. These compounds destroy the lipid layer of cell membranes and damage chloroplast structure. Lead causes irreversible disruption of the photosynthetic apparatus of crops by blocking intracellular antioxidant enzymes. This appears visually as inhibited biomass growth and reduced overall agroecosystem productivity. Arsenic contamination is similarly complex because of its isomorphic similarity to phosphorus. E. Moreno-Jiménez *et al.* (2012) and M. Aide *et al.* (2016) showed that typical natural arsenic content in soils ranged from 5 to 7.5 mg/kg. In ammunition disposal zones, however, arsenic oxides quickly transformed into toxic salts, namely arsenates and arsenites. This inhibited plant cellular respiration through competitive replacement of phosphate ions. The particular danger of arsenic for agroecosystems lies in its specific mechanism of entry into plant tissues. D. Sinha *et al.* (2023) described this process in detail. In the form of arsenate, this metalloid chemically imitates phosphate ions, so the root system passively absorbs it through nutrient channels. Inside the cell, arsenic replaces phosphorus in ATP molecules. This blocks energy metabolism, damages chloroplast cellular structure and slows photosynthesis. Most of the metalloid is usually deposited in the roots. However, more mobile pools can move into above-ground biomass through aquaporin proteins. This causes deep toxic stress and marked inhibition of crop development.

Copper and zinc have similar geochemical characteristics. Both elements are essential trace elements, yet copper and zinc become toxic when background levels are exceeded. Pursuant to K. Oorts (2013), copper

concentration in the lithosphere was around 60 mg/kg, while its accumulation in the arable layer occurred extremely slowly. Precise monitoring of copper concentrations is essential because the boundary between copper as a micronutrient and copper as a dangerous toxicant is very narrow. Copper bioavailability depends strongly on environmental acidity because the ionic form, Cu^{2+} , dominates in acidic soils. In response to such contamination, plants change the composition of root exudates and release phenolic compounds to bind the metal directly in the rhizosphere. Meanwhile, excess copper acts as an antagonist of mineral nutrition and strongly blocks plant uptake of phosphorus, calcium, and manganese (Trentin *et al.*, 2022). F.J.R. Cruz *et al.* (2022) noted that the physiological norm of copper content for higher plants ranges from 2 to 20 mg/kg of dry matter. Exceeding this threshold triggers a cascade of biochemical disturbances. These disturbances damage iron-copper clusters in cells, block redox reactions and inhibit biomass growth. J. Mertens and E. Smolders (2013), together with C. Noulas *et al.* (2018), showed that the background content of zinc usually ranged from 10 to 100 mg/kg and depended strongly on the genesis of the parent rock. Excess zinc presents a serious threat because it is more mobile and bioavailable in the soil solution than many other heavy metals. H. Kaur *et al.* (2024) noted that critical zinc concentrations cause phytotoxicity through destruction of chloroplast ultrastructure and induction of oxidative stress. This leads to chlorosis and leaf necrosis. Excessive uptake of the element also triggers secondary iron and magnesium deficiency because zinc competes strongly with these nutrients for common transport channels on cell membranes.

Nickel occupies a separate place among the analysed elements. A.V. Barker and D.J. Pilbeam (2006) pointed out that its average content in European soils ranged from 3 to 48 mg/kg. The authors showed that exceeding the critical nickel threshold of 100 mg/kg of dry matter caused profound disturbances in stomatal conductance, slowed seed germination and led to generalised chlorosis. J. Kováčik & M. Vydra (2024) summarised data showing that excess nickel provokes deep oxidative stress. It causes prolonged hydrogen peroxide accumulation, destruction of protein molecules and a decline in photosynthetic pigment content. Nevertheless, plant physiological response differs strongly between species. Dicotyledonous crops show much higher tolerance to nickel excess than monocotyledonous crops. Such crops respond to stress by intensively accumulating protective amino acids, particularly proline, as a mechanism of cellular adaptation.

To provide a comprehensive understanding of the risks posed by heavy metal accumulation in agroecosystems, the study summarised the circulation scheme (Fig. 1). Primary metal input caused by hostilities or industrial emissions undergoes transformation in the soil

profile. The mobility of elements is controlled by the physicochemical parameters of the environment. The next stage involves the transfer of bioavailable fractions through the root system into plant tissues, followed by the translocation to assimilatory organs. The

greatest risk arises when these elements reach the final links of the food chain. In addition to it, the migration of chemical elements into plant tissues can negatively affect crop development and produce pronounced phytotoxic effects.

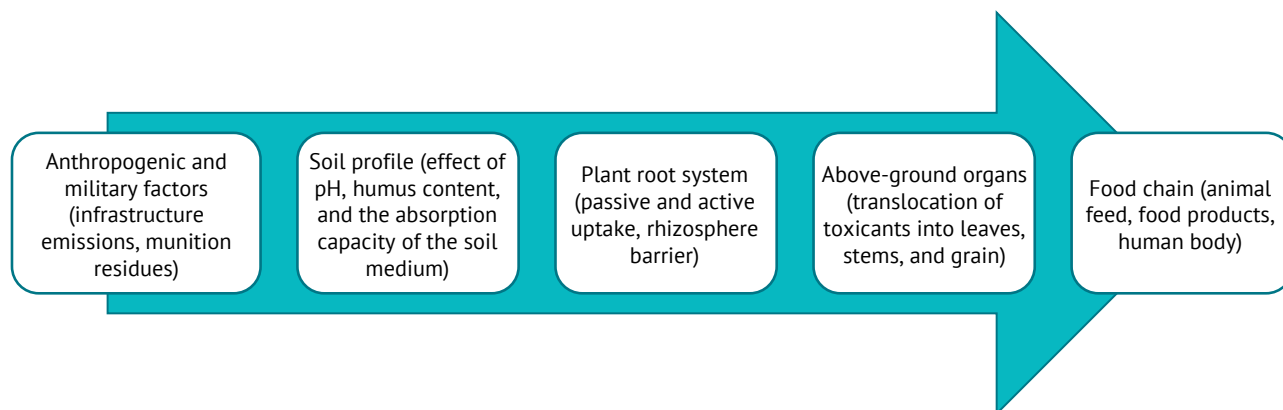


Figure 1. Scheme of heavy metal migration and transformation in the soil–plant–food chain system

Source: developed by the autho

The scheme above shows why the content of chemical elements in agricultural land requires careful control. Even components usually regarded as essential trace elements can cause damage when crops accumulate these components in excessive amounts. In such cases, these elements may harm the environment and enter the trophic chain.

Comparative analysis of phytoremediation strategies and regulatory control of heavy metal content

The practical implementation of soil clean-up measures directly relies on the specific features of national hygienic regulation. This system actually shows a certain imbalance. An analysis of the provisions of Order of the Ministry of Health of Ukraine No. 368 (2013) showed that the content of barium, zirconium, strontium, zinc, copper, and nickel in agricultural products is not currently regulated. This creates considerable environmental risks and calls for the development of preventive biological methods for land remediation. By contrast, strict legal limits exist for lead and arsenic. Pursuant to the same regulatory act, the maximum permissible lead content must not exceed 0.2 mg/kg in cereals and 0.10 mg/kg in vegetable crops. Arsenic content is also strictly limited in rice fields, with values ranging from 0.10 to 0.25 mg/kg depending on the intended use of the product.

The efficiency of metal removal through phytoremediation varies greatly. It depends on the biological characteristics of the plants used as remediators and on the selected strategy, whether phytostabilisation or phytoextraction. A comparison of findings from different authors makes it possible to define several key patterns in metal uptake. P.R.C.D.C. Ribeiro *et al.* (2018)

compared in experiments the potential of *Typha dominigensis* and *Cyperus papyrus* during the clean-up of model ecosystems contaminated with barium. The results revealed a clear difference in remediation mechanisms. Cattail concentrated most of the barium in its roots and followed a phytostabilisation strategy. Papyrus, in contrast, ensured intensive translocation of the metal into above-ground organs. Indian mustard (*Brassica juncea*) showed a similar phytoextraction potential for barium and nickel. According to V.M. Yatsenko *et al.* (2024), barium uptake by mustard during the flowering stage was statistically significant. N. Syam (2022) confirmed that the use of compost additives increased nickel accumulation in mustard plants to 425–455 mg/kg of dry weight by stimulating biomass growth.

Wild-growing and industrial crops proved effective for the remediation of land contaminated with strontium and lead. S. Ali *et al.* (2022) reported that cucumber showed features of a hyperaccumulator of the stable strontium isotope. In the context of lead remediation, G. Testa *et al.* (2023) substantiated the high resistance of industrial hemp varieties, including *Futura 75* and *Kc Dora*. E. Acuña *et al.* (2021) demonstrated that the shrub *Atriplex halimus* was suitable mainly for lead phytostabilisation. Even when citric and fulvic acids increased metal mobility, lead remained locked in the root system and did not move sufficiently into the above-ground biomass.

The remediation of soils contaminated with arsenic, zinc, and copper also depends on soil and climatic conditions, as well as on the ecological specificity of the plants used. T. Mehmood *et al.* (2021) showed that maize (*Zea mays* L.) effectively absorbed arsenic. The researchers also identified a critical pattern:

accumulation was much higher in sandy loam substrates than in heavy clay soils, where the metal was fixed by iron oxides. This conclusion corresponds with the findings of C. Picchi *et al.* (2022). The authors recorded a stable decline in hemp and mustard biomass under stress caused by arsenic contamination. During the remediation of zinc anomalies, E. Soares *et al.* (2021) confirmed the reliability of sunflower (*Helianthus annuus*), which immobilised zinc in the roots. Nevertheless, K.I. Paredes-Páliz *et al.* (2024) showed that the grass

Cortaderia nitida actively transported zinc into the leaves. This made it more suitable for complete phytoextraction. J. Widmer and L. Norgrove (2023) recommended *Plantago lanceolata* L. and *Ricinus communis* L. for copper removal. These plants exceeded the accumulation threshold of 1,000 mg/kg. T. Luo *et al.* (2024) recorded similarly high results for rapeseed (*Brassica napus* L.). For a clearer comparison of the geochemical parameters and biological properties of the analysed elements, a summary comparative table is presented below.

Table 1. Geochemical parameters, legal limits and promising remediator plants for heavy metal soil clean-up

Chemical element	Background content in the Earth's crust, mg/kg	MPC in products according to Order of the Ministry of Health of Ukraine No. 368 (2013), mg/kg	Recommended remediator plants (type of remediation)
Barium (Ba)	425-668	Not regulated	<i>Cyperus papyrus</i> (extraction), <i>Brassica juncea</i> (extraction)
Zirconium (Zr)	~ 300	Not regulated	Limited data / accumulation in roots (stabilisation)
Strontium (Sr)	~ 370	Not regulated	<i>Carduus nutans</i> (extraction), <i>Cucumis sativus</i> (extraction)
Lead (Pb)	~ 14	0.10 (vegetables) – 0.20 (cereals)	<i>Cannabis sativa</i> (extraction), <i>Atriplex halimus</i> (stabilisation)
Arsenic (As)	1.5-5.0	0.10-0.25 (for rice)	<i>Zea mays</i> L. (extraction with addition of compost)
Zinc (Zn)	~ 70	Not regulated	<i>Cortaderia nitida</i> (extraction), <i>Helianthus annuus</i> (stabilisation)
Copper (Cu)	~ 60	Not regulated	<i>Brassica napus</i> L. (extraction), <i>Ricinus communis</i> L. (stabilisation)
Nickel (Ni)	~ 80	Not regulated	<i>Brassica juncea</i> (extraction with addition of compost)

Source: developed by the author

The above data show considerable heterogeneity in the geochemical parameters and regulatory approaches applied to the studied chemical elements. One issue deserves particular attention. Most metals, including Ba, Zr, Sr, Zn, Cu and Ni, are not currently regulated in plant products under Order of the Ministry of Health of Ukraine No. 368 (2013). This is the case despite the high background content in the Earth's crust or the potential ecotoxicity. Strict legal regulation applies only to lead and arsenic. The maximum levels of these elements are clearly differentiated by crop type, for instance from 0.10 mg/kg for vegetables to 0.25 mg/kg for rice. Differentiated biological methods were proposed for the clean-up of contaminated areas. These methods ranged from phytoextraction using hyperaccumulator plants to phytostabilisation with organic amendments or compost.

CONCLUSIONS

To summarise the review, increasing anthropogenic and military pressure on Ukraine's agroecosystems creates an urgent need for effective strategies to restore contaminated land. The study defined several gaps in the Ukrainian regulatory framework. In particular, it pointed to the need to develop comprehensive standards and

maximum permissible concentrations for the elements analysed in this review in agricultural products and animal feed. The absence of clear regulation can create direct risks for food security and the national economy. The regional background concentrations of heavy metals in soils, identified through the literature analysis, indicate that the migration behaviour and toxicity of elements depend strongly on the "age" of contamination and the acidity of the environment.

The analysis showed that phytoremediation is the most promising, environmentally safe and economically justified method of land reclamation. Nevertheless, its effectiveness differs regarding the nature of the toxicant. For mobile and highly bioavailable elements, such as zinc and nickel, as well as for arsenic, which enters cells through phosphate transporters, active phytoextraction turns out to be the most effective strategy. This approach implies the removal of metalloids through the accumulation in above-ground biomass. Phytostabilisation is more appropriate for lead and copper. These elements bind strongly to soil organic matter. This strategy relies on the chemical immobilisation of elements in the rhizosphere through the activation of root exudates and the release of phenolic compounds. The analysis also showed that elemental antagonism

plays a pivotal role in reducing phytotoxicity. In particular, the presence of strontium can act as a protective barrier. It blocks root uptake of the more dangerous cadmium and stimulates cellular antioxidant defence. Further research should focus on a deeper study of the molecular mechanisms of oxidative stress in plants under conditions of combined military contamination. Special scientific value lies in the development of integrated technologies that combine the phytoremediation potential of industrial hemp, sunflower, and macrophytes with the application of environmentally safe amendments, which encompass biochar and limestone materials. Such approaches may optimise soil detoxification under changing climatic conditions.

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CONFLICT OF INTEREST

None.

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Фонові концентрації та стратегії ремедіації важких металів у ґрунтових екосистемах

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Анотація. Актуальність роботи зумовлена значним посиленням антропогенного тиску на земельні ресурси України, що доповнюється наслідками масштабних воєнних дій в рамках дій росії проти України, що тривають з 2022 року: руйнуванням промислової інфраструктури та інтенсивним застосуванням боєприпасів, що спричиняє неконтрольоване накопичення токсичних елементів у ґрунтовому профілі. Метою роботи була систематизація та узагальнення наукових даних щодо природного вмісту барію, цирконію, стронцію, свинцю, миш'яку, цинку, міді та нікелю в земній корі та ґрунтових екосистемах, а також аналіз існуючих стратегій ремедіації забруднених ґрунтів. Для досягнення мети було використано метод критичного аналізу та систематизації наукової літератури. У ході дослідження було систематизовано дані про регіональні фонові концентрації важких металів та ідентифіковано ключові чинники, що визначають їхню рухливість і біодоступність у системі «ґрунт-рослина», зокрема рівень рН, вміст органічної речовини та адсорбційну здатність ґрунту. Також було зафіксовано прогалини в українському законодавстві щодо нормування вмісту ряду досліджуваних металів у сільськогосподарській продукції та кормах, що вказує на потребу оптимізації нормативно-правової бази. На основі аналізу світового досвіду виділено ефективні рослини-гіперакумулятори для очищення ґрунтів: технічні коноплі (для фітоекстракції свинцю й нікелю), соняшник та *Cortaderia nitida* (для цинку), гірчиця сарептська (для барію та нікелю), а також специфічні водні рослини, як-от *potamogeton* та папірус. Доведено, що використання місцевих дикорослих видів, адаптованих до конкретних екологічних ніш, може стати основою для високоефективних та біологічно безпечних стратегій рекультивациі деградованих земель. Практичне значення роботи полягає в обґрунтуванні фіторемедіації як найбільш рентабельного та екологічно нейтрального методу відновлення територій

Ключові слова: геохімічний фон; біодоступність; продовольча безпека; гіперакумулятори; фітостабілізація; фітоекстракція; відновлення родючості