BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg
BG PULSE JOURNAL

UDK: 504.5:628.5:581.526.426

DISTRIBUTION OF HEAVY METALS IN THE ENVIRONMENT AND APPLICATION OF PHYTHOREMEDIATION TECHNOLOGIES REVIEW

Kilichev Shohjahon Shomurod ugli,
Junior Researcher, Institute of Botany,
Academy of Sciences of the Republic of Uzbekistan
Sharipova Vasila Ko'ysinovna ,
Senior Researcher, Institute of Botany,
Academy of Sciences of the Republic of Uzbekistan
Maltsev Ivan Ivanovich,
Senior Researcher, Institute of Botany,
Academy of Sciences of the Republic of Uzbekistan
Saitjanova Umida Shuxratovna,
Junior Researcher, Institute of Botany,
Academy of Sciences of the Republic of Uzbekistan
Turdiyev Doston Ergash ugli
Junior Researcher, Institute of Botany,
Academy of Sciences of the Republic of Uzbekistan
Doi: https://doi.org/10.5281/zenodo.21801892

Abstract: This article highlights the role and significance of phytoremediation processes in the ecological restoration of areas contaminated with heavy metals due to anthropogenic activities. The article provides an extensive analysis of the geochemical sources of heavy metals and the processes of their distribution in the environment under the influence of anthropogenic factors, as well as the toxic effects observed in biotic components. Scientific data on the impact of heavy metals on human health, including the occurrence of various diseases and physiological dysfunctions, are also examined. Additionally, the article discusses stress reactions induced by heavy metals in plants, inhibition of growth processes, and metabolic changes. The fundamental principles and practical foundations of phytoremediation are specifically highlighted, and the physiological and biochemical characteristics of hyperaccumulator plants are scientifically analyzed.

Keywords: Phytoremediation, hyperbatteries, stress effects, heavy metals, toxic effects.

Introduction

Global economic development and industrialization processes are causing serious environmental impacts, especially secondary industrial waste and dispersed particles (dust) emitted by mining and metallurgical enterprises pose a significant environmental threat to the biosphere. Due to rapid industrialization and urbanization, environmental pollution is increasing on a global scale. This situation causes adverse alteration of biological, physicochemical parameters in the atmosphere, hydrosphere, and lithosphere, which ultimately negatively affects biotic components (Sytar et al., 2019).

Environmental pollution includes material changes in the composition of air, water, and soil, which negatively affects their physical, chemical, and biological properties. As a result, there is a

great danger to the vital activity of living organisms, especially animals and plants, which leads to serious environmental problems (Masindi & Muedi, 2018).

Heavy metals and metalloids are a serious environmental problem on a global scale, as they pose a constant threat to public health and wildlife. Unlike organic pollutants, heavy metals cannot be broken down biologically (Valls et al., 2002). They can only be neutralized by converting them into biologically inactive forms or transforming them into less toxic forms. The toxic effects of metals lead to serious physiological changes in living organisms (Boyd, 2010). Studies show that the insolvency of heavy metals in the soil proves the need for more in-depth research in this area (Alloway et al., 2013; Xiaoqi et al., 2017). As biodegradable factors, heavy metals can persist in the soil for a long time and have a persistent toxic effect on ecosystems (Li et al., 2017; Valdes et al., 2014). Despite the widespread use of many metals, they have a significant negative impact on the environment, especially heavy metals can pose a serious threat to environmental systems (Rahman and Singh, 2019; Khan et al., 2002).

Heavy metals are the main pollutant of agricultural soils. At high concentrations, they can negatively affect the development and yield of crops. The toxicity of heavy metals is one of the main abiotic stresses that pose a threat to the health of plants and animals. Due to their high reactivity, they can directly influence the processes of growth, aging, and energy synthesis (Maksymiec et al., 2007). Even the lowest concentration of heavy metals has a toxic effect on living organisms. Pollution of the environment by heavy metals as a result of anthropogenic activity and natural processes is a widespread and serious problem. Heavy metals are found in soil in various forms, and their solubility and biological presence differ significantly. The geochemical movement of heavy metals in the soil, their assimilation by plants, and their influence on yield depend on various physicochemical properties of the soil (Shahid et al., 2015). Therefore, this review summarizes the geochemical and anthropogenic distribution of heavy metals, their toxic effects on plants, animals, and human health, and discusses the basic principles, mechanisms, and practical applications of phytoremediation, with particular emphasis on the ecological significance of hyperaccumulator plants.

Materials and methods

This research is based on bibliometric analysis and a comprehensive literature synthesis, with scientific data obtained from leading scientific databases such as Scopus, Web of Science, and Google Scholar. In the process of analysis, the most relevant and authoritative scientific articles, reviews, and research results were selected using keywords such as phytoremediation, hyperaccumulators, stress effects, heavy metals, toxic effects, and indicators. The collected data were critically evaluated, and their scientific validity, methodological strength, and relevance to the research topic were considered. Further, based on this data, conclusions were formulated on each part of the article, including the mechanisms of hyperaccumulation, types of hyperaccumulators, advantages and limitations of phytoremediation, as well as its ecological significance.

Result

Geochemical sources and anthropogenic distribution of heavy metals

Soil contamination with heavy metals has become a serious problem in many parts of the world (Jing et al., 2016). Although heavy metals are natural components of the Earth's crust, they are constant environmental pollutants and have a huge negative impact on ecosystems (Rice et al., 2014). Heavy metals in agricultural soils, in addition to their natural origin mainly from basic soil materials, are associated with various anthropogenic activities. These include mining, smelting, wastewater irrigation, clay reuse, and the application of agrochemicals. Extremely heavy metals accumulate in the soil through the use of pesticides and fertilizers, improper utilization of industrial

waste, chemical production, metal coating, leatherworking, and atmospheric precipitation, many of which are the result of human activity. (Tang et al., 2019; Mitra et al., 2022; Paschoalini & Bazzoli 2021). Pollution of the mine and its surrounding areas with heavy metals due to metal mining processes leads to a sharp deterioration of ecosystems and significant losses (Kodirov et al., 2017).

Stress reactions of biotic components under heavy metal toxicity

Contamination of water and land with heavy metals is becoming extremely harmful to various life forms, including plants, animals, and microorganisms. The risk of toxic metal pollution increases the threat to the environment and causes disruptions, especially in agriculture, through the accumulation and assimilation of plants from the soil (Shi et al., 2023). Metals are divided into essential and non-essential elements according to their biological role. Although some metals are essential for many biological and metabolic processes in living organisms, their constant entry and accumulation in the food chain has a chronic effect, posing a serious threat to human and animal health. (Yu et al., 2023). Metalloids such as arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), and mercury (Hg) are included in the list of priority metals that pose a great threat to the environment due to their toxic nature. All these substances are systemic toxins; it is known that their effects, even at low concentrations, can harm many organs (Priya et al., 2023; Singh et al., 2023).

Mining activities and coal mining from surface deposits, as well as the utilization of ore and fly ash, lead to significant changes in the landscape. This leads to land degradation, deterioration of air and water quality, almost complete disappearance of plants, and negative impact on fauna and humans (Gajic and Pavlovic, 2018).

Soil contamination with potentially toxic elements is a global problem arising from various human activities, such as industry, agriculture, and the mining industry. This activity releases harmful elements into the environment and poses a threat to ecosystems and human health. These substances affect important soil functions and can lead to stress of plants or crops due to their resistance, toxicity, and easy absorption by plants (Kastner et al., 2025).

Diseases and dysfunctions caused by heavy metals in human health

In ecological systems, heavy metals undergo the phenomenon of biomagnetization along food chains, i.e., their concentration progressively increases with increasing trophic levels. This process causes the impact of high levels of metal compounds on consumers, in particular, on the human population, which significantly increases the risk of serious toxicological and pathophysiological complications (Liu et al., 2018). The concentration of heavy metals emitted into the environment from industrial facilities, the dynamics of their distribution, and the toxic impact on the components of the ecological system (soil, water, air, and biota) remain one of the most pressing ecological and toxicological problems today (Kumar et al., 2019).

The impact of heavy metals on the human body is one of the important reasons for the development of extensive and serious pathological conditions, such as disorders of the central nervous system, kidneys, liver, and respiratory system (Li et al., 2014). Heavy metals interfere with nerve signal pathways and affect various cellular processes such as cell growth, reproduction, survival, metabolism, and apoptosis (table 1). In particular, chromium (Cr) compounds can cause serious pathophysiological consequences, leading to dermal pathologies, cadmium (Cd) to nephropathy and arterial hypertension, and lead (Pb) to neurotoxic disorders and fetal developmental disorders (Sall et al., 2020).

Heavy metals can enter the body through several means, such as ingestion of contaminated food or liquids, inhalation of contaminated air, and absorption into the skin, and have been found to negatively affect a wide range of biological processes (Chounwou et al., 2012). One of the main

mechanisms of the toxic effect of heavy metals is the creation of oxidative stress and the weakening of the antioxidant defense system. They cause an increase in reactive oxygen species (ROS) in cells, which damages cellular components, including lipids, proteins, and DNA. As a result, the activity of enzymes is disrupted, which leads to the disruption of such important intracellular processes as growth, reproduction, differentiation, and damage recovery (Balali et al., 2021). Existing studies show that the toxic effects of heavy metals on the human body can manifest throughout the entire life cycle, from embryonic development to biological death.

Table 1.

Toxicological effects of heavy metals on the human body

№	Metal	Pathogenic effects	Source
1.	Cr	Chromium (Cr) toxicity causes significant damage to the lungs, liver, and kidneys. Changes in the cell structure (ultrastructure) of these organs are observed, which ultimately leads to cell death (apoptosis) in them.	Rituraj et al., 2022
2.	Cd	Cadmium (Cd) exhibits its toxic effects mainly through changes in gene expression, inhibition of the process of restoring damaged DNA, and interference with apoptosis and autophagy. It also increases systolic blood pressure.	Dukic et al., 2020
3.	As	Diabetes mellitus, hyperkeratosis, cancer of various body organs, hypertension, neurodegeneration, skin lesions, impaired cognitive and intellectual function, DNA damage and chromosomal aberration, peripheral neuropathy	John et al., 2022
4.	Hg	Inhibits the production of trypsin, chymotrypsin, pepsin, xanthine oxidase, intestinal mucosa necrosis, gastric ulcer, bloody diarrhea, bronchitis, pulmonary fibrosis, hypothalamic-pituitary-adrenal system disorder	Charkiewicz et al., 2022
5.	Pd	It interferes with DNA transcription, causes fetal loss, inhibits hemoglobin synthesis, and increases the risk of diarrhea, anemia, skin allergies, encephalopathy, osteoporosis, and ventricular hypertrophy.	M. Samuel et al., 2022
6.	Ni	Reproductive toxicity, resulting in cell apoptosis, lung toxicity, inflammatory processes, oxidative stress, respiratory cancer, and genotoxicity.	Genchi et al., 2020

Stress reactions and growth inhibition caused by heavy metals in plants

Any harmful impact on agricultural ecosystems directly harms many intensive physical, chemical, and biological processes that are closely related to the development and productivity of green plants. The main reason for the toxicity of heavy metals in plants is the excessive formation of reactive oxygen compounds (RCO/ROS), which leads to oxidative stress (Romero-Puertas et al., 2019). A certain concentration of heavy metals in the affected areas can be absorbed by plants (Wang et al., 2018). At the same time, these heavy metals induce serious pathophysiological disorders in the plant organism, limiting growth and development by inhibiting their fundamental physiological processes (Aydinalp et al., 2009; Chen et al., 2022; El-Sappah et al., 2022; Lee et al., 2023). Heavy metals in the soil are first absorbed by the root system of plants, and then translocated to the above-ground organs. Therefore, the part that is primarily affected by heavy metals is mainly the root (Podar and Maathuis, 2022). Studies have shown that heavy metals also

inhibit the reproductive processes of plants. In particular, these metals negatively affect plant development by disrupting the physiology of seed germination and reducing their ability to absorb water (Osman and Fadxallah, 2023). In particular, experiments aimed at studying the effect of lead (Pb) on the plant organism have confirmed its harmful effect on many physiological processes (Collin et al., 2022). Ecotoxic concentrations of heavy metals lead to profound disruption of vital processes in plant organisms (table 2). These disorders are characterized by a weakening of metabolic mechanisms, which can even lead to complete loss of cellular activity (Singh et al., 2015). In plant cells exposed to heavy metals, oxidative stress is induced, which leads to the degradation of cell membranes and lipid peroxidation (Emamverdian et al., 2015).

Table 2.

Influence of heavy metals on phytocenoses

№	Metal	Pathogenic effects	Source
1.	Pb	DNA damage disrupts lipid oxidation and ATP production. They reduce the rate of photosynthesis, inhibit chlorophyll synthesis, and lead to the closure of stomata. Q lead (Pb) negatively affects seed germination, root growth, and cell division.	Rahman et al., 2024 Ilyas et al., 2024
2.	Cd	It reduces the activity of metal-sensitive enzymes, slows seed germination, and leads to leaf abscission and chlorosis. Metals also inactivate starch mobilization in the endosperm, reducing the mitotic division of meristematic cells.	Alebgebawy et al., 2021 Fasih et al., 2021
3.	Ni	It alters the function of the enzyme, which prevents seed germination and growth. Additionally, it binds to pectin, reducing the elasticity (plasticity) of cell walls, consequently limiting root growth.	Hassan et al., 2019
4.	Sr	High concentrations lead to the drying of stem cells and the separation of the plasma wall. This condition slows down plant development, disrupts homeostasis, and affects the dynamic balance of the antioxidant enzyme system. As a result, the growth of the hypocotyl and epicotyl parts of plants is inhibited.	Saud et al., 2022
5.	As	It has harmful effects such as chlorosis, cell death, disruption of mineral homeostasis, epinasty, and necrosis. As a result, biomass decreases and the rate of photosynthesis slows down. They also cause genetic changes such as micronuclear production, aneuploidy, chromosomal abnormalities, chromatid metabolism, deletion mutations, and DNA-protein binding.	Sinha et al., 2023
6.	Hg	It disrupts enzymatic activity, inhibits chlorophyll synthesis, and negatively affects photosynthesis, transpiration, and water absorption. They also strongly bind to the protein's sulfhydryl/thiol groups, leading to protein structural disruption.	Gworek et al., 2020

Metals and metalloids constitute the main class of environmental pollutants on a global scale, posing a serious threat to plant growth and ontogenesis (Sharma et al., 2020). Under conditions of metal and metalloid stress, significant morphophysiological changes are observed in the tissues of the root cortex of plants. These include structural disorders in endodermal cells, deposition of suberin and lignin, thickening of exodermal and endodermal cell walls, formation of air cavities, and changes in the composition of intercellular spaces. As a result, changes also occur in the internal parenchymal cells of the roots, which is sometimes accompanied by the formation of deposits in various parts of the plant's body. These changes in cell structure and function are not limited to the root system; they spread from the root tissues, disrupting cell division and the expansion of cortical cells. (Clemens et al., 2016; Yadav et al., 2021).

Phytoremediation: basic principles and practical foundations

Reclamation of soils contaminated with heavy metals is a global environmental problem, and numerous studies are being conducted to address it (Susan et al., 2018). Researchers are testing methods such as chemical stabilization, heat treatment (pyrolysis and vitrification), electroremediation, soil replacement, chemical precipitation, and chemical leaching in field conditions. These approaches are important in ensuring the ecological safety of soils and restoring their fertility. However, physicochemical methods have a number of limitations, they have high economic costs, and their effectiveness decreases at low concentrations of pollutants. Moreover, these methods can lead to irreversible changes in the physicochemical and biological properties of the soil and even cause secondary pollution (Ali et al., 2013).

Therefore, there is a need to develop and implement both effective and economically viable, sustainable reclamation technologies for the reclamation of soils contaminated with heavy metals. This is a prerequisite not only for protecting the environment from heavy metals, but also for restoring the natural fertility of the soil and developing sustainable agricultural practices. Future research should focus on innovative approaches to solving these problems, in particular, nature-based solutions such as bioremediation and phytoremediation (Hasan et al., 2019).

Phytoremediation is a biological purification method (Rigoletto et al., 2020) based on the use of plants to remove, decompose, or neutralize various environmental pollutants, in particular heavy metals and organic compounds, from a contaminated environment (soil, water, and air) (Sun et al., 2017, Ashraf et al., 2019). Plants have different genotypes capable of neutralizing heavy metal stress (Das et al., 2021). This technology is distinguished by its environmental efficiency and economic feasibility. One of the main advantages of phytore remediation is its ability to minimize the formation of secondary pollutant residues. Unlike traditional physicochemical cleaning methods, chemical reagents or high-energy processes are not used in the phytoremediation process, which significantly reduces the risk of the formation of new, toxic substances after cleaning. Pollutants are absorbed, accumulated, broken down, or stabilized by plants. Subsequently, the contaminated plant biomass is safely collected and disposed of.

Phytoremediation is carried out without destroying the natural structure of the soil, while preserving its biological activity, and at the same time serves to increase the ecological and aesthetic value of contaminated areas. Numerous experimental studies have shown that phytoremediation demonstrates stable positive results in neutralizing a wide range of contaminants, such as hydrocarbons, chlorinated solvents, pesticides, heavy metals, and landfill filters. These data scientifically substantiate the importance of this technology as an effective and promising solution in protecting the environment from pollution. The term phytoremediation consists of the Greek prefix "phyto," which means "plant," and the Latin root "remedium," which means "treatment or cleansing of the disease" (Cunningham et al., 1996).

Phytoremediation approaches offer a wide range of strategies for cleaning pollutants from the environment (table 3). These strategies include several main approaches, each of which has its own specific mechanisms, areas of application, advantages, and challenges (Khan et al., 2022).

Table 3.

Main types and principles of phytoremediation

№	Phytoremediation parts.	Process Description	Source
1.	Phytoextraction	Plant absorption of pollutants from the soil by the roots and their accumulation in the above-ground parts (stems and leaves). This biomass is then collected and disposed of.	Cao et al., 2025
2.	Phytostabilization	Use of plants to reduce the mobility of pollutants in the soil. This process prevents metals from seeping into groundwater or spreading through air by immobilizing them.	Pankaj et al., 2023
3.	Phytodegradation	Soil microorganisms with the help of exudates released from plant roots decomposition of organic pollutants by stimulating their activity.	Arjun et al., 2022
4.	Rhizofiltration	Absorption, adsorption, or deposition of pollutants in water bodies through plant roots. This is mainly done in hydroponic systems.	Arjun et al., 2022
5.	Phytovolatilization	How plants absorb pollutants (such as volatile compounds like mercury or selenium) through their roots and release them into the atmosphere in volatile form through their leaves.	Khushbu et al., 2024

Plants have formed new, adaptive, and accurate methods for resisting the harmful effects of heavy metal stress in these areas of phytoremediation. (Tiwari and Late, 2018). This mechanism includes various strategies, such as immobilization, extraction from the plasma membrane, restriction of absorption and transport, synthesis of specific heavy metal carriers, induction of stress proteins, and chelation and sequestration by specific ligands (Adrees et al., 2015). Plants are divided into three categories based on their survival strategies in unfavorable conditions: accumulators, excluders, and indicators (Baker, 1981). Accumulative plants play a key role in cleaning the soil from harmful factors, particularly heavy metals. Such plants are known to science as hyperaccumulators of the flora.

Hyperaccumulative plants: Physiological characteristics and ecological significance

The term hyperaccumulator was first introduced in 1976 and serves to scientifically describe plant species capable of accumulating certain elements (mainly heavy metals) in their tissues at concentrations hundreds or even thousands of times higher than normal concentrations in the environment. These plants have a unique biological ability to absorb and accumulate elements from the soil in an unnaturally large quantity.

Plants undergo hyperaccumulation of heavy metals, as a result of which more than 0.1%-1% of the dry weight of metals accumulate. For example, Baker and Brooks (1989) used the term "hyperaccumulator" for plants with leaf nickel concentrations above 1000 mg/g. The following

criteria for the concentration of hyperaccumulation are proposed for various metals and metalloids in dry plant tissues growing in a natural environment: 100 mg/kg for cadmium (Cd), selenium (Se), and titanium (Ti); 300 mg/kg for copper (Cu), chromium (Cr), and cobalt (Co); 1000 mg/kg for arsenic (As), nickel (Ni), and lead (Pb); 3000 mg/kg for zinc (Zn); and 10000 mg/kg for manganese (Mn) (Yang et al., 2019). Since phytoremediation methods can take decades to restore contaminated areas, long-term monitoring of the soil-vegetation system is necessary (Rathod et al., 2013). Only about 0.2% of the world's higher plant population exhibits a hyperaccumulatory phenotype (Jin and Qian, 2019).

To date, more than 700 taxons of hyperaccumulative plants have been identified, and this list is constantly expanding (Reeves et al., 2018). These plant groups are considered the most alternative way to purify the ecosystem from heavy metals and restore the natural state of the soil. Hyperaccumulative plants can effectively absorb and transfer metals from their roots to their stems and leaves, isolating and neutralizing them in their cell walls and vacuoles. In particular, the metals accumulated in the vacuoles are stored in contact with organic acids or other compounds, which ensures the protection of the plant from toxic effects (Memon, 2016). Hyperaccumulative plants play an important role in ensuring the stability of the ecosystem; they have the ability to purify the soil (bioremediation) by absorbing heavy metals from contaminated areas into their bodies, which is carried out while preserving the natural state of the soil. At the same time, they also have the property of detoxifying heavy metal ions (Yang et al., 2021). Among the well-known families of plants with hyperaccumulative properties are Asteraceae, Brassicaceae, Buxaceae, Cunoniaceae, Euphorbiaceae, Flacourtiaceae, Phyllanthaceae, Rubiaceae, Salicaceae, and Violaceae (Zhang et al., 2020). Hyperaccumulative plants absorb toxic elements from the soil, significantly improving soil quality, which increases the environmental safety of agricultural lands and expands the possibilities of their use .

Acknowledgment. This research was supported by the State Programs “Digital Nature. Development of a digital platform for the flora of Central Uzbekistan”, implemented by the Institute of Botany of the Academy of Sciences of the Republic of Uzbekistan for the period 2025-2029".

Conflict of interest. Authors declare that there is no actual or potential conflict of interest in relation to this article

Conclusion

In conclusion, the most effective and optimal solution for restoring the ecological state of territories polluted as a result of various mining and industrial activities is the use of phytoremediation processes and hyperaccumulative plants. This approach helps restore the natural state of the environment by cleaning soil and water bodies from heavy metals and other harmful substances. Hyperaccumulative plants are the main driving force of the bioremediation process by accumulating metals in their tissues and neutralizing them.

However, to ensure the full effectiveness of the phytoremediation process, it is necessary to compile a list of hyperaccumulating plants specific to the region and develop additional strategies to increase their metal-absorbing capacity. These strategies should be aimed at stimulating plant growth, optimizing metal transfer to the plant, and accelerating the remediation process. A deeper study of the mechanisms of heavy metal assimilation by hyperaccumulative plants in the soil and

increasing their genetic potential will lay the foundation for finding more effective solutions for the restoration of polluted ecosystems in the future.

References

1. Adrees M., Ali S., Rizwan M., Ibrahim M., Abbas F., Farid M., Bharwana S.A. (2015) The effect of excess copper on the growth and physiology of important food crops: a review. Environmental Science and Pollution Research, 22 (11): 8148–8162.
2. Ali H., Khan E., Sajad M.A. (2013) Phytoremediation of heavy metals – concepts and applications. Chemosphere, 91 (7): 869–881.
3. Alloway B.J. (2013) Sources of heavy metals and metalloids in soils. In: Alloway B.J. (ed.) Heavy Metals in Soils. Dordrecht, Springer, p. 11–50.
4. Arjun K., Anil T., Asmita G., Kaushik A., Anukul B., Niroj A. (2022) Phytoremediation: mechanisms, plant selection, and enhancement by natural and synthetic agents. Environmental Advances, 8: 100203.
5. Ashraf S., Ali Q., Zahir Z.A., Ashraf S., Asghar H.N. (2019) Phytoremediation: an environmentally sustainable way to reclaim heavy metal-contaminated soils. Ecotoxicology and Environmental Safety, 174: 714–727.
6. Aydinalp C., Marinova S. (2009) The effects of heavy metals on seed germination and plant growth on the alfalfa plant (Medicago sativa). Bulgarian Journal of Agricultural Science, 15 (4): 347–350.
7. Baker A.J. (1981) Accumulators and excluder-strategies in plants' response to heavy metals. Journal of Plant Nutrition, 3 (1–4): 643–654.
8. Baker, A. J. M., & Brooks, R. (1989). Terrestrial higher plants which hyperaccumulate metallic elements. A review of their distribution, ecology and phytochemistry. *Biorecovery.*, *1*(2), 81-126.
9. Balali-Mood M., Naseri K., Tahergorabi Z., Khazdair M.R., Sadeghi M. (2021) Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. Frontiers in Pharmacology, 12: 643972.
10. Boyd R.S. (2010) Heavy metal pollutants and chemical ecology: exploring new frontiers. Journal of Chemical Ecology, 36: 46–58.
11. Cao X., Dong Q., Mao L., Yang X., Wang X., Zou Q. (2025) Enhanced phytoextraction technologies for the sustainable remediation of cadmium-contaminated soil based on hyperaccumulators – a review. Plants, 14 (1): 115.
12. Charkiewicz, A. E., Omeljaniuk, W. J., Garley, M., & Nikliński, J. (2025). Mercury Exposure and Health Effects: What Do We Really Know? International Journal of Molecular Sciences, 26(5), 2326. https://doi.org/10.3390/ijms26052326
13. Chen L., Beiyuan J., Xu V., Zhang Z., Duan C., Cui Q., Fang L. (2022) Phytoremediation of soils contaminated with potentially toxic elements (PTE) using alfalfa (Medicago sativa L.): a comprehensive overview. Chemosphere, 293: 133577.
14. Chounwou P.B., Yedjou C.G., Patlolla A.K., Sutton D.J. (2012) Heavy metal toxicity and the environment. In: Molecular, Clinical and Environmental Toxicology. Volume 3: Environmental Toxicology. p. 133–164.
15. Clemens S., Ma J.F. (2016) Toxic heavy metal and metalloid accumulation in crop plants and foods. Annual Review of Plant Biology, 67: 489–512.
16. Cunningham S.D., Ow D.W. (1996) Promises and prospects of phytoremediation. Plant Physiology, 110 (3): 715–719.