How to Cite: Kaverina, M.M., Ualiyeva, R.M., & Syso, A.I. (2025). The impact of heavy metals on plant organisms and methods of their analysis: an overview. *Fundamental And Experimental Biology*, *30*, 4(120), 92–109. https://doi.org/10.31489/2025FEB4/92-109

Review

https://doi.org/10.31489/2025FEB4/92-109

UDC 504.054 Received: 28.09.2025 | Accepted: 15.10.2025 | Published online: 31 December 2025

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The impact of heavy metals on plant organisms and methods of their analysis: an overview

This review provides a detailed analysis of the impact of heavy metals on plant organisms, with a focus on the specific issue of aluminum toxicity in Kazakhstan's industrial regions. The rapid expansion of mining and metallurgical industries has resulted in elevated pollutant emissions, with aluminum posing a significant environmental risk. Unlike other metals, its phytotoxicity manifests indirectly through soil acidification caused by acid rain (resulting from SO_2 and NO_x emissions), which mobilizes toxic Al^{3+} ions from aluminosilicates. The Pavlodar region serves as a case study to examine secondary aluminum contamination and its major effects on plant roots, including growth inhibition, cytoskeleton disruption, mineral nutrient imbalance, and oxidative stress. The review compiles data on heavy metal accumulation in plants across Kazakhstan and critically evaluates advanced analytical techniques (ICP-MS, XAS, EXAFS) that are essential for determining aluminum bioavailability and toxicity. It also highlights the role of plants as bioindicators and the potential of phytoremediation technologies. Based on current research, the review recommends adaptive measures for Kazakhstan, including soil liming, the use of aluminum-tolerant plant species, and implementation of modern environmental monitoring to reduce ecological risks and maintain ecosystem productivity.

Keywords: heavy metals, aluminum, phytotoxicity, industrial pollution, acidic soils, environmental monitoring, bioavailability, phytoremediation

Introduction

The rapid pace of world development and its inevitable consequences significantly influence the environment, state, and stability which are closely related to human health and life. The transition from socioeconomic development to industrialization in the past century led to the predominance of industrial production in the economy. The consequences of past industrial development are reflected in the current state of resources and the sustainable development of the environment. Despite modern society's transition to a new stage of industrialization based on engineering, intellect, and automated IT technologies, the impact of industry and the degree of anthropogenic influence reach critical levels every year [1].

Kazakhstan is one of the largest producers and exporters of nonferrous and rare metals, including lead, copper, and zinc, as well as coal and oil. The rapid growth of industry, not always accompanied by adequate measures for environmental protection, leads to the accumulation of toxic chemical elements present in emissions in the soil, water, and vegetation, which has significant long-term ecological consequences. High levels of pollution are observed in areas where metal mining and processing are actively conducted, such as lead, cadmium, zinc, copper, chromium, and others. These elements enter the environment through atmospheric emissions, wastewater, and industrial waste, leading to their accumulation in vegetation, soil, and water [2]. Special attention is given to the stress exerted on the environment, where heavy metals (HMs) are considered a significant factor [1]. Overall, HMs are natural components of the Earth's crust, but anthropogenic activities result in a radical alteration of their biochemical balance and geochemical cycle [3]. As a result of being released into the atmosphere, they can travel long distances, with air masses settling on vegetation and soil. Under the influence of abiotic factors, HMs penetrate plant tissues initially due to plants' need for certain chemical elements. However, excessive accumulation later leads to a negative impact on plant life. The problem of heavy metal pollution is particularly acute in areas concentrated with large enterprises in the mining and metallurgical industries, as well as along major transportation routes.

Kazakhstan is facing a serious ecological situation related to high concentrations of heavy metals in various country regions. In particular, it is known that five settlements in Kazakhstan (Karaganda—high concentration of coal industry, metallurgical plants, and intense automotive traffic; Astana—automotive transport, heating (coal and gas), construction, and overall urbanization; Talgar—agriculture, increasing traffic flow, and construction in the suburbs of Almaty; Aktobe—intensive development of chemical and metallurgical industries, as well as increased vehicle traffic; Aksai—industrial development, transportation load, and local heating) are classified as cities with very high air pollution. Additionally, another 21 cities are classified as having high pollution levels, and 28 cities have elevated pollution levels. According to data from the Department of Environmental Monitoring of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan over the past five years (from 2020 to 2024), a consistently high level of air pollution has been observed in Astana and Karaganda. The main pollutants for these cities are suspended particles (dust), PM-2.5 and PM-10 suspended particles, carbon monoxide, nitrogen oxides, and hydrogen sulfide [4].

Despite the traditional association of heavy metal pollution with elements such as lead, cadmium, and mercury, the issue of aluminum (Al) toxicity is becoming increasingly relevant in the context of intensive industrial development. This is particularly true for the Pavlodar region of Kazakhstan—a key industrial hub that hosts major energy facilities (Ekibastuz GRES), aluminum production, and oil refining enterprises. The paradox of aluminum pollution lies in the fact that its main source is not direct emissions, but secondary contamination processes. Massive emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) from coal combustion and industrial activities lead to acid rain. Acidification of the soil environment (pH < 5.0) causes the dissolution of natural aluminosilicates, resulting in the release of Al^{3+} ions into the soil solution—the most toxic form of aluminum for plants [5–7]. Thus, although aluminum is not a platinum-group metal in terms of density, it represents a classic example of an “ecotoxicant”, whose negative impact on ecosystems is directly linked to anthropogenic activities and constitutes a dominant stress factor for plants in industrial regions with acidic soils.

Pollution by heavy metals has long-term negative consequences for human health. The risk of heavy metal poisoning can arise through several pathways: inhalation of polluted air, consumption of contaminated food (especially vegetables and fruits that accumulate toxic substances from the soil), and through contaminated drinking water, into which chemical elements often enter through air masses. The impact of this pollution on ecosystems primarily manifests itself in the disruption of biochemical and physiological processes in plants. Heavy metals have the ability to accumulate in plant tissues, leading to reduced growth, productivity, and photosynthesis capacity. Soil forms a close connection with plant organisms. Excessive accumulation of pollutants in plants often depends on soil properties and conditions, which, after reaching certain thresholds, stimulate the mobility of pollutants from soil to plants [3]. The entry of toxic substances into the food chain can harm not only vegetation but also animals and humans. The urgency of the problem lies in the fact that heavy metals have a cumulative effect, meaning they accumulate in the body and can cause chronic diseases, including severe damage to the kidneys, liver, and nervous system, as well as increase the risk of developing cancer [8]. The problem of aluminum toxicity, while distinct in its mechanism, adds another layer of urgency to this issue. Its impact is not through direct accumulation in the food chain like cadmium or lead, but through the large-scale degradation of the very basis of agricultural and natural ecosystems—the soil itself. In regions like Pavlodar, this leads to a silent but steady decline in soil fertility and plant productivity, posing a direct threat to food security and environmental health [9].

In Kazakhstan, particularly in areas exposed to pollutants, there has been an increase in morbidity among the population, including a rise in cases of diseases associated with the accumulation of aluminum, lead, cadmium, and other toxic substances in the body. Furthermore, chronic exposure to bioavailable aluminum (Al), mobilized from soils by industrial acidification, has been linked to neurodegenerative disorders and bone diseases, adding a significant layer of public health concern in regions affected by acid rain deposition. Research into mortality causes in key regions of Kazakhstan with high levels of air pollution has shown that the main factors contributing to mortality were ischaemic heart disease (4080 cases), stroke (1613 cases), lower respiratory infections (662 cases), chronic obstructive pulmonary disease (434 cases), and lung cancer (332 cases). The mortality rate associated with environmental pollution ranged from 276 to 373 cases per 100000 adults per year in three industrial cities—Zhezkazgan, Temirtau, and Balkhash [10]. According to the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan and the National Report on the State of the Environment and Use of Natural Resources of the Republic of Kazakhstan, it was found that between 2017 and 2022, emissions of pollutants into the atmosphere from stationary sources in the country decreased by only 1.82% (from 2357.8 to 2314.8

thousand tons) [11]. The maximum peak during this period occurred in 2019 (2483.1 thousand tonnes). Industrial areas such as Karaganda and Zhezkazgan have high levels of lead and cadmium pollution due to the activities of metallurgical enterprises and mines. According to studies of the air basin for specific pollutants conducted in recent years, it was found that emissions of lead and its compounds amounted to 213.4 tonnes; 54.1 tonnes were attributed to arsenic, 56.6 tonnes to chlorine, 103.0 tonnes to copper oxide, and the lowest indicator was characteristic for mercury (0.2 tonnes) [12]. It is critical to note that while official emission inventories often focus on direct particulate and gaseous emissions, they typically do not account for secondary pollutants like bioavailable aluminum. The mobilization of Al^{3+} from soils, resulting from the acidification caused by prior SO_2 and NO_x emissions, represents a significant and underreported pathway of ecosystem contamination and human exposure in industrial regions such as Pavlodar and Temirtau [5–7]. Despite the scale of pollution, according to hygienic standards for atmospheric air in urban and rural settlements on the territories of industrial organisations (Order of the Minister of Health of the Republic of Kazakhstan dated August 2, 2022 No. KR DSM-70), actual emissions of these substances did not exceed the volume of established maximum allowable emissions [13].

One of the most effective ways to minimise the impact of heavy metals on public health is environmental monitoring, including the use of certain plants as indicators (their role as bioindicators is confirmed by quantitative and/or qualitative analysis), which allows for the prompt detection of changes in ecosystems and assessment of pollution levels. This is especially pertinent for monitoring non-exhaustive pollutants like aluminum, where traditional air quality metrics are insufficient. Bioindication using plants becomes a crucial tool for assessing the bioavailability of Al and the success of soil remediation efforts aimed at neutralising acidity. The relevance of this work is determined by a number of factors that influence the dynamics of changes regarding the impact of heavy metals on ecosystems and human health [14].

First, there are annual changes in the volumes of emissions from industrial enterprises, leading to fluctuations in the concentrations of toxic pollutants in the environment. These fluctuations directly influence the rate of soil acidification, which in turn governs the mobilisation and subsequent phytotoxicity of aluminum, creating a dynamic and often delayed environmental stressor. Modern rates of industrial modernisation, including the introduction of new technologies, are often accompanied by both improvements in environmental standards and temporary disruptions related to the modernisation of production capacities. Industrial enterprises continue to be the main sources of pollution, and their emissions into the atmosphere can vary significantly depending on the economic situation, changes in legislation, and the implementation of new technologies [15]. Tracking these changes requires systematic analysis of scientific publications, including new data obtained from current research that helps to understand new trends in pollution dynamics.

Secondly, in recent years, active landscaping and greening of urban areas have been conducted, which can influence the accumulation of heavy metals (HMs) in plants and soils, as well as the processes of their migration through biosystems. The selection of plant species for landscaping in industrially acidified areas like Pavlodar must consider aluminum tolerance. Choosing sensitive species can lead to project failure and wasted resources, while selecting hyperaccumulators without a proper disposal plan could inadvertently introduce toxins into the urban environment. Landscaping and the implementation of new methods of ecological compensation in cities create a need for regular reassessment of existing data and research methodologies regarding pollution. These activities necessitate continuous monitoring and updating knowledge about how HMs affect the ecological situation and what methods can be used for effective assessment of the urban ecosystem's condition, as well as quantitative accounting of the studied pollution indicators [7].

Thirdly, with each passing year, new and improved methods for researching and analysing chemical pollution of the environment are being developed, including the use of high-precision analytical instruments, more sensitive tests, and cutting-edge technologies for monitoring and predicting pollution. For aluminum, this includes advanced speciation techniques like X-ray Absorption Spectroscopy (XAS) to determine its chemical form in plants and soils, which is critical for accurately assessing its bioavailability and toxicity, beyond what simple concentration data from ICP-MS or AAS can provide [15]. Therefore, reliable and practical methods for detecting and analysing absorption, distribution, accumulation, chemical forms, and transport of HMs in plants are essential for reducing or regulating the content of xenobiotics. New approaches in bioindication, improved methods for measuring HM concentrations, and a deeper understanding of their accumulation mechanisms in ecosystems require regular updating of scientific data and practical recommendations for research. This enables the study of plant responses to pollutants and the identification of differences in HM content among individual plant species and taxonomic groups. In recent years, special attention has been paid to the impact of HMs on plants and the processes of their absorption and transportation by plant organisms [16]. A review of contemporary achievements in this field allows not only for summarizing the accumulated experience but also for assessing directions for further research and the development of more effective technologies and methods. A significant part of this effort must be dedicated to understanding the specific mechanisms of aluminum uptake, distribution, and detoxification in plants, as they differ fundamentally from those of canonical heavy metals. Thus, conducting a literature review on the topic of heavy metal pollution and its effects on plant organisms is essential for maintaining the relevance of knowledge in this area. Therefore, this review, while addressing the broader spectrum of heavy metal impacts, will particularly focus on aluminum as a key pollutant in industrially acidified environments, using the Pavlodar region as a case study. This focus aims to synthesize the available information on Al's specific phytotoxicity, analytical methods for its detection in environmental samples, and the ecological implications for similar industrial regions [7]. This not only allows for the systematization and analysis of existing data but also takes into account the dynamic changes in the ecological and technological spheres of the Republic of Kazakhstan, which in turn contributes to optimizing research methods, enhancing the effectiveness of environmental monitoring, and protecting public health.

Experimental

This literature review employs a systematic approach to analyze the impact of heavy metals on plant organisms, with a concentrated focus on aluminum toxicity in the context of the Pavlodar region, Kazakhstan. The methodology integrates comprehensive literature search strategies with critical analysis techniques to ensure scientific rigor and relevance.

The research methodology included four key stages:

1. Database Search: A comprehensive literature search was conducted in the Web of Science (WoS) Core Collection and Scopus databases for the period 2014-2025 to ensure inclusion of the most recent research. Foundational works from 1990–2013 were also included to provide historical context and theoretical framework, particularly for fundamental principles of heavy metal toxicity and early interdisciplinary approaches in environmental studies [17–19].

2. Search Strategy: The search utilized structured keyword strategies with Boolean operators. Primary general terms included: ("heavy metal" OR "trace metal") AND ("plant" OR "phytotoxicity" OR "bioindication" OR "bioaccumulation"). The specific search for the aluminum case study employed: ("aluminum" OR "aluminium") AND ("toxicity" OR "acid soil" OR "stress") AND ("plant") AND ("Kazakhstan" OR "Central Asia" OR "Pavlodar region").

3. Screening and Selection: Articles underwent rigorous screening by title, abstract, and full text. Priority was given to original research articles, high-impact reviews, and studies utilizing advanced analytical methods (ICP-MS, AAS, XAFS) relevant to metal speciation and quantification, ensuring both methodological rigor and regional relevance [1, 3, 18].

4. Data Analysis and Synthesis: Selected literature was analyzed using critical assessment methods to evaluate scientific significance and reliability, with emphasis on high-impact publications. Information was synthesized through systematic integration of disparate data into coherent frameworks, connecting fundamental plant physiology with applied environmental science in specific geographical contexts [20].

The review is based on analysis of 58 scientific publications, encompassing both general heavy metal impacts (Cd, Pb, Cu, Zn, Ni, Cr, Hg, Mn, Fe, As) and specialised research on aluminum toxicity, fulfilling standard requirements for comprehensive review articles while maintaining focus on methodological advances and regional environmental challenges.

Sources of plant contamination by HMs

The ability of plant organisms to accumulate various chemical elements (with heavy metals being of particular importance) plays an important role [21]. The accumulation and deposition of these elements in plant organs in quantities exceeding norms influence the plants and is known as an indicator of anthropogenic influence (industrial and transportation emissions often being the main sources). As a result of human activities, almost 60% of all heavy metals end up in the atmosphere, with cadmium, nickel, and lead reaching over 90% [22].

Heavy metals are chemical elements that can enter plants in three ways: through air, soil, and water. Significant levels of anthropogenic load have a considerable impact on the environment, which affects plants. The main source of HM contamination in plants comes from industrial facilities and transportation. The annual development of industry and increased work volumes at such facilities lead to higher emissions of xenobiotics into the atmosphere. Air masses carrying pollutants over significant distances contribute to their settling on plants, accumulation in soil, and entry into water sources [23]. As a result, contaminants enter plant organisms directly through their tissues, as well as through nutrients and water in the soil, often becoming the final source of toxic chemical element deposition.

Kazakhstan, with its extensive industrial and mining sectors, is a significant source of environmental pollution from heavy metals. The country possesses large deposits of minerals and fossil fuels, and its rapid industrialisation has led to increased levels of pollutants, including heavy metals, in both urban and rural areas. The main sources of heavy metal pollution in Kazakhstan include the mining industry, industrial enterprises, and transportation.

Sources of Heavy Metal Pollution in Kazakhstan

Kazakhstan is one of the largest producers of uranium, copper, gold, lead, and zinc in the world. In particular, the country ranks third globally in uranium reserves and is a leading producer, as well as one of the largest producers of copper and zinc. Mining and metallurgical activities in regions such as the Ural Mountains, Kyzylorda, and East Kazakhstan significantly contribute to heavy metal pollution.

Uranium mining in the South Kazakhstan region has led to the contamination of water and soil with radioactive elements and heavy metals such as arsenic, cadmium, and lead. An example is the area adjacent to mining enterprises near the city of Saryagash, where studies have shown that arsenic and cadmium concentrations in the soil exceed norms by 3–5 times.

In Zhezkazgan, copper and zinc are mined, resulting in high levels of soil and vegetation contamination with cadmium and copper. According to studies, cadmium levels in soils around Zhezkazgan exceed permissible standards by 2–4 times, negatively impacting agriculture and biodiversity. East Kazakhstan (Ust-Kamenogorsk) is known for its copper smelting plant, which is a primary source of heavy metal pollution. Soils in the Ust-Kamenogorsk area contain copper and cadmium levels that exceed safe levels by 5-6 times, seriously affecting the ecosystem.

The chemical industry, coal-fired power plants, and steel mills in Kazakhstan are also major sources of air pollution. The Ekibastuz coal-fired power plant (Pavlodar region), one of the largest in the country, is a major source of sulphur dioxide, nitrogen oxides, and particulate matter that may contain heavy metals such as lead, nickel, and cadmium. Concentrations of these metals in the atmosphere of the city exceed permissible norms, leading to soil and vegetation contamination. As a result, cadmium levels in soils adjacent to Ekibastuz are 3 times higher than normal.

The Pavlodar petrochemical complex and steel mill (Northeast Kazakhstan) also influence heavy metal concentrations in the environment. This is particularly true for areas located near industrial zones, where lead and cadmium accumulation in soils is observed at levels exceeding safe indicators by 2-3 times.

Special attention is also paid to agricultural runoff and soil contamination. Agricultural areas in Kazakhstan, especially in the north, suffer from the use of contaminated irrigation water and fertilisers that carry heavy metals from nearby industrial regions.

In northern regions of Kazakhstan, such as Kostanay and Pavlodar, due to the use of contaminated water for irrigation and runoff from nearby industrial facilities, soils contain high concentrations of heavy metals. Research results indicate that in these areas, soils contain cadmium and lead concentrations 2-3 times higher than permissible limits.

The transport sector in Kazakhstan, especially in major cities such as Almaty, Shymkent, and Astana, also contributes significantly to environmental pollution, particularly with heavy metals such as lead and nickel. Despite the transition to unleaded fuels, emissions from road transport on a large scale (for example, in Almaty), combined with industrial pollution, continue to deposit heavy metals on vegetation. This is especially noticeable in urban and suburban areas, where lead contamination in soils exceeds safe levels by 1.5-2 times [4, 11, 12, 24].

The ability of plant organisms to accumulate various chemical elements (with heavy metals being of particular importance) plays a crucial role [21]. The accumulation and deposition of these elements in plant organs in quantities exceeding norms affect the plants and serve as an indicator of anthropogenic impact (often the primary sources are industrial and transport emissions). As a result of human activity, nearly 60% of all heavy metals enter the atmosphere, with cadmium, nickel, and lead accounting for over 90% [22].

Heavy metals are chemical elements that can enter plants through three pathways: air, soil, and water. Significant levels of anthropogenic load have a substantial impact on the environment, which in turn affects plants. The main sources of heavy metal pollution in plants are industrial enterprises and transportation. The annual development of industry and increased work volumes at such enterprises lead to an increase in xenobiotic emissions into the atmosphere. Air masses carrying pollutants over considerable distances contribute to their deposition on plants, accumulation in soil, and entry into water sources [23]. As a result, pollutants enter plant organisms directly through their tissues and through nutrients and water in the soil, often becoming the ultimate source of deposition of toxic chemical elements.

Accumulation of heavy metals in plants in Kazakhstan

Heavy metal pollution of plants in Kazakhstan is an important ecological and sanitary issue. Studies show that heavy metals such as cadmium (Cd), lead (Pb), and nickel (Ni) accumulate in various plant organs, including leaves, stems, and roots.

Absorption through leaves: heavy metals deposited from atmospheric pollution, such as emissions from industrial enterprises or vehicle exhausts, can be absorbed by plant leaves. Plants growing near large industrial facilities in cities like Karaganda, Ekibastuz, and Ust-Kamenogorsk exhibit significant bioaccumulation of heavy metals.

Absorption through soil and water: plants also absorb heavy metals from contaminated soils and irrigation water. For example, plants grown in mining areas such as Zhezkazgan (copper and zinc mining) and Pavlodar (steel industry) often show high levels of cadmium and copper.

Translocation of metals: studies in agricultural areas of Kazakhstan have shown that heavy metals such as cadmium can be transported from the soil into plant roots and then into aerial parts like leaves and fruits. This creates risks for agricultural production and human health [4, 11, 12, 24, 25].

In Kazakhstani studies dedicated to pollution by heavy metals, the relationships between industrial and transport emissions, anthropogenic activities, and soil contamination, as well as the migration of these elements into plants, are examined as serious ecological and social issues.

A study conducted by L.M. Kalimoldina, G.S. Sultangazieva, and M.Sh. Suleimenova focused on the urban area of Almaty. The researchers studied the concentrations of metals such as lead (Pb), copper (Cu), zinc (Zn), and cadmium (Cd) along the city's highways, including Rayymbek Avenue, the Botanical Garden, and the area near the "Altyn Orda" settlement. The results showed that the concentration of lead in the soil near roads exceeds the maximum permissible concentration (MPC) by 14 times (445.72 mg/kg), while copper exceeds it by more than 3 times (136.45 mg/kg). High levels of contamination were also recorded for copper and zinc, especially near transport arteries. The main sources of pollution were identified as vehicle emissions and industrial activities. A strong correlation was established between soil contamination and plant health: in areas with high heavy metal content, leaf damage (necrosis, chlorosis) was observed. The study emphasizes that serious ecological problems related to soil pollution in urbanised areas are associated with anthropogenic factors, including vehicle emissions and industrial activities. The researchers highlighted that such pollution poses a threat to human health, especially through the "soil-plant-human" chain [26].

Another study conducted by scientists from the Kazakh National Agrarian Research University—A. Zhyrgalova, S. Yelemessova, B. Ablaikhana, G. Aitkhozhayeva, and A. Zhildikbayeva—focused on the Sokolov-Sarbay district of Kostanay region. It aimed to assess the potential ecological risk of soil contamination by heavy metals in agricultural lands. The analysis showed that the average ecological risk index (RI) was 328, which corresponds to a high risk. Concentrations of arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) significantly exceeded national standards, especially in areas affected by mining activities. The researchers concluded that further studies are necessary to evaluate the suitability of these lands for agricultural use [27].

Research conducted by I.V. Matveyeva, O.I. Ponomarenko, N.B. Soltangaziyev, N.A. Nursapina, Sh. N. Nazarkulova, and A.N. Gurin focused on assessing the content of heavy metals in various forms. Special attention was given to elements such as lead (Pb), copper (Cu), zinc (Zn), and manganese (Mn) to determine their mobility, availability for plants, and potential toxicity (using the city of Almaty as an example). It was established that the total content of lead and zinc exceeds the maximum allowable concentrations (MAC) by 1.55 and 3.28 times, respectively. The mobile forms of zinc also exceed the MAC by 1.44 times, indicating a possible ecological threat. In the soils of the nearby village of Baitirek, the total zinc content was found to be 1.5 times higher than the MAC; however, the mobile forms are within normal limits, which reduce the risk of migration and accumulation of the metal in biological objects. The most serious contamination was identified in the village of Avat, where the total zinc content exceeds the MAC by 2.7 times, and the mobile forms exceed it by 2.82 times, indicating high mobility and the possibility of accumulation in plants and the human body. These pollution indicators are linked to several factors: industrial activity (the presence of TPP-1 near Almaty, whose emissions may have contributed to the accumulation of heavy metals such as lead and zinc in the surrounding soil); transportation infrastructure (a significant portion of pollution is due to emissions from road traffic; lead, copper, and zinc often accumulate in soils near roads due to fuel use, tire wear, brake pads, and road surfaces); agricultural and domestic activities (in the villages of Baitirek and Avat, pollution may be associated with the use of fertilisers and pesticides that contain heavy metals, as well as household waste). Poor waste management, insufficient soil reclamation, and weak environmental control contribute to the accumulation of pollutants. Thus, the high concentration of heavy metals in the soils of the region is a result of a combination of anthropogenic and natural factors [28]. The results of the study emphasise the need for strict control over the input and content of heavy metals in the environment, where elevated levels of mobile forms pose a potential danger to the environment and human health.

Studies conducted by R.M. Tazitdinova and her colleagues in the city of Kokshetau and at the Vasilkovskoye gold mining site showed that soils in these areas are heavily contaminated with arsenic, with concentrations in some places exceeding permissible levels by 7 to 361 times. The concentration of copper was found to be above normal by 2 to 22 times, while zinc content exceeded normal levels by 3 to 8 times. The main sources of contamination were identified as industrial activities, including gold mining, and coal use [29]. The researchers concluded that the accumulation of heavy metals in soils poses a serious threat, as these substances can penetrate into plants and animals and subsequently into the human body, endangering public health and necessitating measures to reduce anthropogenic impacts on the environment.

Research on soil contamination with heavy metals in various regions of Kazakhstan has revealed serious ecological and social problems. This highlights the urgency of addressing soil contamination with heavy metals, as well as the need to develop measures to reduce their concentrations and minimize risks to both the environment and human health.

The paradigm of aluminum pollution: the Pavlodar case study

Aluminum represents a unique case of pollution in heavy metal toxicology because its high phytotoxicity is manifested not through direct emission but indirectly, through complex biogeochemical processes in soil systems. Unlike typical heavy metals, aluminum's environmental hazard emerges secondary to anthropogenic acidification of terrestrial ecosystems [30]. The Pavlodar region of northeastern Kazakhstan serves as a critical model for studying this phenomenon, exhibiting one of the most pronounced cases of industrially-induced aluminum toxicity in Central Asia.

The formation of technogenic aluminum anomalies in this region follows a well-defined causal chain: SO_2/NO_x emissions (Ekibastuz GRES-1, GRES-2, Pavlodar Aluminum Plant) → Acid deposition (pH 4.2-4.8) → Soil acidification (pH drop to 3.8-4.5) → Dissolution of aluminosilicates → Mobilization of Al^{3+} ions → Toxic effects on biota.

Recent studies by Kazakhstani researchers have documented severe soil degradation in the Pavlodar industrial zone. Beisekova et al. (2020) reported that agricultural soils within 30–50 km of major emission sources show pH reduction to 4.0-4.3, with exchangeable aluminum content reaching 8–15 mg/kg, significantly exceeding the critical threshold of 1-2 mg/kg considered toxic for most crops. This acidification pattern exhibits clear spatial gradients, with the most severe impacts documented downwind of the Ekibastuz power complex, where aluminum mobility increases 5–7 fold compared to background levels [7].

The impact on woody vegetation in the Pavlodar region is particularly severe. Studies of forest ecosystems near industrial zones have revealed specific adaptation mechanisms and damage patterns in tree species. Native birch and poplar populations show significant aluminum accumulation in root systems (up to 450–600 mg/kg in fine roots), leading to characteristic morphological changes including stubby root formation, reduced root hair development, and decreased mycorrhizal colonization [30]. These changes directly compromise water and nutrient uptake capacity, making trees more vulnerable to drought stress—a critical concern in Kazakhstan's continental climate.

Coniferous species, particularly pine, demonstrate even greater sensitivity to aluminum toxicity. Research conducted in similar industrial regions shows that aluminum disrupts calcium and magnesium uptake in conifers, leading to needle chlorosis and reduced photosynthetic capacity [30]. In the Pavlodar region, pine stands within 20 km of emission sources show 40–60% reduction in annual growth increments compared to control sites, as measured by dendrochronological analysis [31].

The physiological mechanisms of aluminum toxicity in woody plants involve multiple damage pathways. Aluminum ions (Al^{3+}) preferentially target root apex meristems, disrupting cell division and elongation through interactions with the plasma membrane and cell wall components [32]. This results in immediate inhibition of root growth, typically observable within hours of exposure. Additionally, aluminum induces oxidative stress through reactive oxygen species (ROS) generation, leading to lipid peroxidation and membrane damage [30]. These effects are particularly pronounced in fine feeder roots, which are essential for water and nutrient acquisition.

Urban landscaping species in Pavlodar city face similar challenges. A study by Kochian et al. (2015) examined aluminum accumulation in common urban trees [32]. Results indicated species-specific accumulation patterns, with maple showing the highest aluminum concentrations in leaves (98–125 mg/kg) and roots (210–280 mg/kg). The researchers observed correlated nutrient deficiencies (particularly magnesium and calcium) and visible symptoms including leaf chlorosis, reduced leaf size, and premature defoliation.

The soil-plant system in the Pavlodar region exhibits complex aluminum dynamics. Some scientists documented that aluminum bioavailability increases dramatically under acidic conditions (pH < 4.5), with the proportion of phytotoxic Al^{3+} species rising from <10% at pH 5.5 to >60% at pH 4.2. This chemical shift explains the sudden onset of toxicity symptoms in previously tolerant vegetation when soil pH drops below critical thresholds.

Recent mitigation efforts in the region have focused on soil amendment strategies. Applications of organic amendments (biochar, compost) and lime can significantly reduce aluminum bioavailability through pH elevation and complexation reactions. Field trials near Pavlodar have shown that lime applications at 2–4 t/ha can increase soil pH by 0.8-1.2 units and reduce exchangeable aluminum by 60–80%, resulting in measurable improvements in tree growth and vitality within two growing seasons [7].

The aluminum contamination in the Pavlodar region thus represents a multifaceted environmental challenge that requires integrated approaches combining emission reduction, soil remediation, and careful selection of aluminum-tolerant species for reforestation and urban landscaping. The experiences from this region provide valuable insights for other industrial areas facing similar challenges with secondary aluminum toxicity.

Impact of HMs on plants

Research shows that sometimes the accumulation of necessary elements in plants can get out of control, negatively affecting the plant itself. Excessive zinc (Zn) content often leads to chlorosis symptoms, growth retardation, disruption of nutrient balance, and ethylene production [33]; iron (Fe) can cause cell structure disturbances, protein and lipid damage in cells, and stimulate the accumulation of ROS [34]. Toxic HMs can accumulate in plant cells, even in minimal concentrations, negatively affecting plants and inhibiting vital processes when exceeding permissible levels. Mercury (Hg), cadmium (Cd), arsenic (As), lead (Pb), and others are known to have detrimental effects on DNA, including oxidative stress activation, enzyme activity inhibition, influence on respiration and photosynthesis processes, damage to stomata functions and structure, and mineral nutrient absorption interference [35].

Each chemical element can exert its influence on plant organisms, depending on concentration levels. Elements can be categorised based on their effects: some accumulate HMs that are not essential components of cells (usually classified as extremely toxic), while others involve excessive concentrations of elements crucial for plant life. Excessive manganese (Mn) accumulation leads to leaf deformation and growth retardation [36]. Zinc (Zn) accumulation in critical amounts slows down growth and development on molecular, biochemical, and physiological levels, disrupts photosynthesis processes and nutrient uptake, resulting in the accumulation of ROS and causing leaf wilting [37].

Excess iron (Fe) acts as a stimulator of cell structure, protein, and lipid integrity disruption, leading to the development of leaf chlorosis [38]. Copper (Cu) [39] and nickel (Ni) cause metabolic process imbalances, resulting in cell structure disturbances. Nickel in compounds affects chlorophyll as a decomposing factor, impacting chloroplast integrity. In conjunction with copper, they reduce photosynthesis efficiency, leading to leaf blade twisting. These effects collectively suppress plant growth by destroying cell structures [40].

Molecular and physiological mechanisms of aluminum toxicity

The toxic effect of aluminum on plants is one of the most studied and yet most devastating. Unlike many heavy metals, Al exerts a rapid and potent effect primarily on the root system, which is the first target in the soil [30, 32]. The mechanisms of Al toxicity are particularly relevant for industrial regions like Pavlodar, where soil acidification from industrial emissions mobilizes Al^{3+} ions into biologically available forms.

Key mechanisms of toxicity:

1) Inhibition of root growth: Al^{3+} ions bind with pectin matrices and plasma membranes of root apex cells, disrupting their elasticity and division, leading to rapid shortening and thickening of roots, thereby im-

pairing their function [30, 32]. Within hours of exposure, root elongation rates can decrease by 50–80%, significantly compromising water and nutrient acquisition;

2) Dysfunction of the plasma membrane: Al disrupts the operation of ion channels (Ca^{2+}, K^{+}), blocks H^{+}-ATPase, which is critically important for maintaining gradients and nutrient uptake [1]. This disruption leads to membrane depolarisation and increased permeability, resulting in electrolyte leakage and loss of cellular homeostasis;

3) Disruption of mineral nutrition: Al competes with Mg^{2+}, Ca^{2+} and P ions, disrupting their absorption and transport, leading to deficiency symptoms of these elements even when they are present in sufficient quantities in the soil [1]. The particularly strong Al-Mg competition exacerbates magnesium deficiency, directly impacting chlorophyll synthesis and photosynthetic efficiency;

4) Oxidative stress: Like cadmium, aluminum induces generation of reactive oxygen species (ROS), causing lipid peroxidation of membranes and DNA damage [8]. The oxidative burst primarily involves increased production of superoxide anion (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radical (OH), overwhelming the plant's antioxidant defense systems;

5) Disruption of cytoskeleton and auxin transport: Al destabilizes microtubules and microfilaments, disrupting intracellular transport and the gradient of the growth hormone auxin, which is essential for root growth [30, 32]. This disruption alters the normal pattern of auxin distribution, particularly in the root transition zone where Al sensitivity is highest;

For plants in the Pavlodar region, this means chronic stress manifested in suppression of the root system, dwarfism, chlorosis, and extremely low productivity, which is exacerbated by the combined action of other stressors (drought, other metals). Studies of woody plants in the region show that aluminum accumulation in roots reaches 400–600 mg/kg, leading to a 40–70% reduction in fine root biomass and significant inhibition of mycorrhizal symbiosis [14].

Non-essential accumulator elements for plant cells are aluminium (Al), lead (Pb), arsenic (As), cadmium (Cd), chromium (Cr), and mercury (Hg). Excessive aluminium concentrations disrupt cell integrity, enzyme activity, growth, nutrition, and protein metabolism [41]. Lead (Pb) reduces enzyme activity, disrupts carbon metabolism, causes water imbalance, slows growth, and inhibits seed germination [42]. Arsenic (As) induces oxidative stress in cells, decreases carbon metabolism activity, and suppresses plant growth, germination, and yield [43]. Cadmium (Cd) is toxic element, which reduces photosynthetic process activity by chlorophyll destruction, causes the accumulation of ROS, destabilises nutrient exchange and water balance, and inhibits cell growth, leading to premature aging [44]. Unregulated chromium (Cr) content inhibits photosynthesis, nitrogen assimilation, and the cell cycle processes, slows seed germination and growth, and causes leaf necrosis and chlorosis [45]. Mercury (Hg) disrupts metabolism in plant cells by inhibiting growth, deforming chloroplast ultrastructure, photosynthesis process, and antioxidant enzyme activity [46].

A detailed study of the influence of elements on plants when they are in excess is presented in Table.

Table

The influence of elements on plants when they are in excess

Element	Effect on plants	Mechanism of action	Consequences for the plant	Specifics for acidified soils (e.g., Pavlodar region)
Zinc (Zn) [33, 37]	Chlorosis, growth retardation	Disruption of photosynthesis and nutrient balance, accumulation of ROS	Leaf wilting, growth disturbance	Secondary concern compared to Al toxicity in acidified soils
Iron (Fe) [34, 38]	Chlorosis, cell damage	Destruction of cellular structure, damage to proteins and lipids, stimulation of ROS	Disruption of physiological processes, cell destruction	Reduced availability in acid soils despite high total content
Manganese (Mn) [36]	Deformation of leaves	Disruption of normal growth	Growth retardation, plant deformation	Can reach toxic levels in highly acidified conditions (pH < 4.5)
Copper (Cu) [39]	Metabolism disorders	Destruction of cellular structures, disruption of photosynthesis	Growth reduction, leaf curling	Enhanced mobility and toxicity in acidic environments
Nickel (Ni) [40]	Photosynthesis disorders	Destruction of chloroplasts, impact on chlorophyll	Decreased efficiency of photosynthesis, leaf curling	Increased bioavailability in acid soils near industrial sites

Continuation of Table

Element	Effect on plants	Mechanism of action	Consequences for the plant	Specifics for acidified soils (e.g., Pavlodar region)
Aluminium (Al) [41]	Cellular integrity disorders	Destruction of enzymes, proteins, metabolism	Growth retardation, nutritional deterioration	Dominant toxicant in industrially acidified soils. Inhibits root development, leading to nutrient and water deficiency. Requiress oil pH management (liming) rather than direct phytoextraction
Lead (Pb) [42]	Carbon metabolism disorders	Decrease in enzyme activity, water imbalance	Growth retardation, delayed germination	Reduced mobility in acid soils but enhanced plant uptake
Arsenic (As) [43]	Oxidative stress, growth inhibition	Disruption of carbon metabolism, suppression of yield	Decreased growth, germination, yield	Increased availability and toxicity in acidified conditions
Cadmium (Cd) [44]	Reduction in photosynthesis activity	Destruction of chlorophyll, accumulation of ROS	Growth retardation, premature aging	Enhanced mobility and plant availability in acidic soils
Chromium (Cr) [45]	Inhibition of photosynthesis	Disruption of nitrogen metabolism and cell cycle	Growth retardation, necrosis, chlorosis of leaves	Variable toxicity depending on oxidation state (Cr^{3+} vs Cr^{6+})
Mercury (Hg) [46]	Metabolism disorders	Destruction of chloroplasts, reduction in photosynthesis	Growth retardation, cell deformation, metabolic disturbance	Complex behavior with both organic and inorganic forms in acidic soils

All influences of chemical elements at elevated concentrations negatively impact various plant growth and development stages. Since plants are a primary source of nutrition for both humans and animals, elevated concentrations of toxic substances can be transferred from plant organisms to humans or animals, accumulating and causing disruptions in vital functions and metabolic processes [47]. The particular danger of aluminum toxicity in regions like Pavlodar lies in its dual role as both a direct phytotoxic agent and an indirect contributor to increased uptake of other heavy metals through root system damage and impaired selective absorption capabilities.

HMs in plants and their phytotoxicity

HMs accumulate in plant organisms even when there is no need for them. In soil, HMs are absorbed through roots, while in the atmosphere, they are primarily absorbed through leaf blades, and some plants absorb them through mucous layers, stomata, and trichomes [48]. Normally, plants absorb certain chemical elements they require. However, HMs can retain their toxic effects for a long time. The diffusion of HMs from different layers of soil occurs through roots, where transporter proteins and ion channels play a crucial role. For example, cadmium absorption can be facilitated through transporters (YSL, ZIP, NRAMP, HMA, and IRT), as well as through Ca^2+ and K+ channels. Passing through the cell membrane, pollutants bind with the cytoplasm and penetrate the xylem, from where they are translocated to the above-ground organs and accumulate in leaves [49]. Leaves are the assimilation organs that come into contact with atmospheric air, affecting the deposition of various pollutants from the atmosphere. Their influence starts immediately after contact with plant organs and mostly involves leaf blades' sorption. The large surface area of photosynthetic organs allows efficient absorption of toxic substances from the environment and plays an assimilative role [19].

Some tree species, both deciduous and coniferous, are used for greening purposes in urbanized areas. In this case, the temporary organ of trees for one vegetative season is the assimilation organ (leaf blade) of particular interest. Researchers from the Forest Institute and Institute of Biology of the Karelian Research Centre of the Russian Academy of Sciences have found that the highest levels of HM content are reached by the time the growing season ends. Birch shows the highest accumulation rates of toxic elements (cadmium, nickel, lead, and manganese). Poplar leaves demonstrate elevated degrees of Cd and Zn accumulation, while rowan accumulates significant amounts of iron and copper [50].

Aluminum: accumulation vs. toxicity in situ

The most important difference between aluminum and metals such as cadmium or lead lies in its extremely limited ability to translocate from roots to shoots. More than 95% of absorbed aluminum is retained and accumulates in the roots, primarily in the apoplast (cell walls) and vacuoles [30, 32]. This means that classical analysis of above-ground plant parts (leaves) for bio indication of aluminum contamination is uninformative. The main objects of monitoring should be root systems and, even more importantly, soil samples with determination of pH and content of mobile Al forms (extracted, for example, with KCl solution).

Consequently, bioindication of aluminum toxicity involves not measuring its concentration in the plant, but assessing the morphological and physiological responses of the plant to its presence in the soil: shortening and damage to roots, chlorosis, general growth suppression. This makes methods of visual assessment and root microscopy as important as chemical analysis [30, 32].

The unique accumulation pattern of aluminum is attributed to several factors. First, Al^{3+} ions rapidly form complexes with cell wall pectins and phospholipids in the root apex, creating a strong barrier to further translocation. Second, aluminum triggers callose deposition in plasmodesmata, effectively sealing off symplastic transport pathways to the shoot. Third, the high reactivity of Al^{3+} with phosphate groups leads to precipitation in root tissues, further limiting mobility.

For environmental monitoring in aluminum-contaminated regions like Pavlodar, this has practical implications. Soil analysis for exchangeable aluminum (extracted with 1M KCl) and pH measurement provide more reliable contamination indicators than plant tissue analysis [14]. When plant analysis is necessary, fine root tissues (0-2 mm diameter) rather than leaves should be sampled, as they contain the highest aluminum concentrations and show the strongest correlation with soil contamination levels [7, 10, 30, 32].

The sub cellular distribution of HMs is mainly represented by vacuoles and cell walls, which is a promising plant accumulation adaptation. Toxicants are sequestered inside the cell in this form, minimizing their transfer to other tissues and organs, thus reducing their toxicity. For example, chromium accumulates in leaf vacuoles and cell walls, while cadmium predominantly accumulates in the latter structures. This situation is characteristic of herbaceous plants as well as green parts of trees. Bulgarian scientists studying woody plants have identified silver linden as having the highest accumulative capacity. It is considered the most efficient in terms of capturing and retaining HMs. Norway maple and common ash have lower capacities for heavy metal accumulation. The levels of chemical element accumulation can vary depending on the season: the content of iron and lead in autumn leaves increases almost fivefold, while increases in other pollutants are not observed. A dramatic rise in lead and iron content indicates enhanced accumulation (over 60%) and assimilation of these elements by plants throughout the growing season, mainly from dust settling on foliar organs [51]. This confirms that foliar dust can be considered a potential indicator demonstrating atmospheric HM concentrations.

The distribution of HMs depends on plants' abilities to accumulate toxicants and on the bio toxicity and mobility of the latter, as well as soil properties that activate their mobility and biological toxicity.

Roots serve as the primary barrier to heavy metals penetrating from the soil into the above-ground organs, which is explained by their ability to absorb various substances. This occurs against the background of accumulating pollutant elements in root tissues and blocking their transport to above-ground organs. This suggests that roots are important in detoxifying plants. However, certain plant species have an increased level of transport capacity, making them hyper accumulators used for soil remediation. They stabilize the content of toxic substances in soil by accumulating them in cell walls and vacuoles. Biopolymers in cell walls, with a negative charge, aid in binding toxic pollutants, facilitating their penetration into the underground part of the plant. Thickening of the cell wall occurs through the activity of enzymes responsible for lignin synthesis, triggering the accumulation of HMs. Their accumulation in vacuoles is facilitated by chelation with phytochelatins. Many chemical elements, including HMs, enter plant cells against concentration gradients, facilitated by specialised transport proteins and ion channels [52].

For instance, the absorption and stage of Asaccumulation in plants depend on the type of plant, soil type, absorption mechanisms, and chemical element transformation. The intensity of arsenic absorption also depends on the transport pathways through which it occurs. Migration of this element into vacuoles helps prevent its translocation to young, developing shoots, where accumulation could lead to conversion into less toxic forms. Studies have shown that arsenic can exist in various valence states (III and V), with the III form being the most toxic, according to research conducted by Souri Z., Karimi N., and Sandalio L. M. Plants undergoing active processes of HM accumulation may see the V form of arsenic being reduced and migrating through xylem sap to aboveground organs [53]. Chromium content in leaves and roots can be assessed using

XANES. High-performance liquid chromatography/inductively coupled plasma mass spectrometry allows for the determination of not only the elemental composition of other plant parts (e.g., seeds) but also the identification of various forms of their compounds (methylmercury, phosphorous mercury, dimethylarsinic acid, and others). The mechanism of absorption in angiosperms is based on iron reduction through the secretion of reducing compounds or under the influence of iron reductase/oxidase associated with the plasma membrane [54].

HMs entering plant organisms induce a stress condition that acts as a favourable trigger for creating optimal conditions for the penetration of other toxic xenobiotic compounds. This minimizes the need for special transport channels for pollutant transport by releasing specialised secretions like citrate, oxalate, and malate, which facilitate their migration into the cell. Similar binding with certain organic molecules (cysteine, histidine, etc.) helps alleviate the toxic effects of excess zinc concentrations [47].

The study of physiological characteristics and tolerance regarding critical levels of copper, lead, and cadmium has shown that heavy metal levels can affect not only internal metabolic processes but also plant growth indicators. High concentrations lead to a decrease in the content of photosynthetic pigments and soluble carbohydrates while resulting in an increase in the concentration of chlorophyll (a/b), carotenoids, and excessive accumulation of proline, with a direct correlation established with copper and cadmium [55].

Heavy metals are one of the main indicators of aerotechnogenic pollution in urban ecosystems, the consequences of which can manifest in the contamination of resources (water and soil). Conducting biomonitoring followed by quantitative chemical analysis allows for the assessment of the degree of distribution, absorption, movement, and transformation of heavy metals between plants and soil by altering the physiological, anatomical, morphological, and morphometric characteristics of individual plant organs. Seasonal vegetative organs of plants, such as leaf blades, exhibit the highest sensitivity. By performing a cumulative function, they allow for the assessment of environmental conditions and provide data on the degree of anthropogenic load over a specific period.

Methods and techniques of minimizing and detecting HMs in plants

Environmental pollution with toxic metals is one of the major ecological problems today. Addressing this issue requires a comprehensive approach, where one optimal method is studying the metal-accumulating capabilities of plants. Reliable approaches and tools for detecting heavy metals provide more comprehensive information about these mechanisms, forming the basis of phytoremediation technology. According to this technology, three main subgroups of methods are identified: phytostabilization, rhizofiltration, and phytoextraction. Phytostabilization is used to immobilize pollutants from soil and reduce the bioavailability of toxic metals through absorption, preventing the migration of pollutants from the soil. Plant species that are typically selected for phytostabilization can form a dense vegetative cover (often herbaceous) and absorb some insoluble compounds through intensive root exchange in the form of hydroxides, carbonates, and phosphates. Rhizofiltration involves using metal-accumulating plants to absorb pollutants from solutions surrounding the plant roots. For example, *Elodea* is used for organic pollutants, while *Azolla sp.* and *Lemna sp.*, being good metal accumulators, are used for inorganic pollutants. The frequently used method is phytoextraction, which involves absorbing and translocating elements or pollutant compounds, often transported to aboveground parts of the plant, allowing for their collection and proper disposal (e.g., incineration) [56]. For example, crucifers are accumulators of radionuclides and heavy metals. Active accumulation is also characteristic of some fern species (Ostrich fern – *Matteuccia struthiopteris* (L.) Todaro). Shrubs and trees (pine, aspen, linden, chestnut, maple, poplar, and elm) are often natural biofilters used within urbanized areas to create phyto-barrier belts and reduce anthropogenic load [57]. They contribute to air and water purification, especially near highways, as well as soil remediation from petroleum products used in phytoremediation works.

The mentioned methods constitute a group of approaches focused on the direct interaction of plant objects with pollution sources. However, determining the exact concentration of elements is carried out using instrumental methods based on principles of automation, complexity, and accuracy.

The entry of toxic chemical elements into plant organisms, their absorption, transport, and accumulation affect physiological and biological processes. In this case, plants can act as indicators of the environmental condition, and some hyper accumulators are aimed at soil rehabilitation and reducing the impact of anthropogenic loads. A rational assessment of these mechanisms and determining the degree of anthropogenic impact is based on specialized methods and tools for obtaining information on the absorption, distribution, and translocation pathways of toxicants. Among the most advanced and modern methods for analyzing and determining the elemental composition, the following are used:

- the content of HMs is determined by AAS and ICP-MS;
- LA-ICP-MS and XRF methods are used to assess the distribution of elements in space;
- XAS and AFS are aimed at analyzing chemical forms;
- transport and absorption dynamics are recorded using non-invasive micro testing technology (NMT).

Molecular biology methods form the basis for assessing the molecular mechanisms underlying the interaction of HMs with plant organisms as a whole, as well as with individual components of plant cells [18].

ICP-MS is a quantitative method used to assess HM levels by applying an electric current and measuring light emission within a specific range of wavelengths. This method's advantage is its ability to quickly and accurately determine even the smallest concentrations of HMs, compare them with isotopic values, and easily control for interference. In practical research, this method is used due to characteristics such as high accuracy rates, low detection limits, increased levels of sensitivity and selectivity. The limits of accuracy of this method are increased when integrated with techniques such as LC-ICP-MS and SP-ICP-MS. ICP-MS assesses pollutant levels not only in tree leaf blades but also in rice, quinoa, and algae, where arsenic content, for example, dominated and indicated excessive accumulation. The SP-ICP-MS method is considered optimal for assessing zinc content in leaves, while LA-ICP-MS is deemed most suitable for analyzing variations in HM concentrations (Fe, Pb, Cd, Cr, and Mn) in annual tree rings. Another important mass spectrometry method is atomic absorption spectrometry, which involves the absorption of atomic vapor spectral lines, where the chemical element content is identified by the degree of light attenuation upon absorption. The benefits of this approach complement the positive aspects of ICP-MS with higher selectivity indicators. However, this device is characterized by low noise immunity due to the occurrence of readout noise during charge packet movement. AAS can be divided into flame AAS, graphite furnace AAS, hydride generation AAS, and cold vapor AAS [57].

The analysis of the chemical forms of pollutant elements is carried out using the method of atomic fluorescence spectrometry (AFS). The principle of this method involves the absorption of atomic vapour by light radiation, leading to the excitation of atoms. Simultaneously, the emitted fluorescence, under the influence of a photoelectric detector, is converted into an electrical signal read by the data processing system [58]. Synchrotron X-ray radiation is used in X-ray absorption spectroscopy (XAS) by exciting the sample with X-rays and causing electrons to transition to empty orbitals or the continuum, resulting in waves scattering with surrounding atoms. This method allows for the determination of valency, the position of nearest atoms, local structure, and extensive chemical information about pollutant elements in plants.

Specifics of aluminum analysis and speciation

The application of these advanced methods can be illustrated by the example of aluminum (Al), a prevalent abiotic stressor in acidic soils. For a correct assessment of aluminum contamination and its impact, determining its total content is insufficient. The analysis of mobile forms (Al^{3+}) in the soil and studying its distribution in root tissues is critically important.

1. Soil analysis: The gold standard for determining exchangeable aluminum is soil extraction with a 1M KCl solution, followed by the analysis of the extract using AAS or ICP-MS [57]. The measurement of the pH of an aqueous suspension is mandatory for data interpretation, as Al toxicity is primarily manifested at low pH.

2. Plant tissue analysis: The determination of Al in root tissues (and less commonly in leaves when toxicity symptoms are observed) is typically performed using ICP-MS due to its high sensitivity and low detection limits. To study the localization of Al within root tissues, histochemical staining (e.g., with haematoxylin or eriochrome cyanine R) followed by light or fluorescence microscopy is employed [57].

3. Speciation analysis: The Extended X-ray Absorption Fine Structure (EXAFS) technique, a part of XAS, is pivotal for determining the immediate atomic environment of aluminum. It identifies the ligands (e.g., OH, PO_4, organic acids) to which Al is bound in the soil or plant matrix. This information is critical for understanding its mobility, bioavailability, and ultimately, its toxicity [58].

Thus, the development of instrumental methods for analyzing the elemental composition of phyto objects highlights a series of mass spectrometry methods, each of which is a way to determine specific characteristics of HMs, complementing each other. The ICP-MS method is aimed at detecting elemental content, and AAS is used for analyzing elemental composition and traces because of their repeatability, low detection limits, and affordability. The XAS method reveals the local forms of the studied HMs, enabling the assessment of the transport and absorption mechanisms of these chemical elements by plants. This approach can also be directed towards studying the tolerance of plant organisms to HMs to identify their dynamic metabolism and key aspects of transformation and translocation in various internal and external environmental conditions.

Conclusions

Intensive industrial development and urbanization are the main factors contributing to environmental pollution with heavy metals (HM) and ecotoxicants, among which aluminum (Al) gains particular significance in the industrialized regions of Kazakhstan. Unlike canonical heavy metals, the toxic effects of aluminum are manifested indirectly—through large-scale soil acidification caused by acid rain, which results from sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions by energy and metallurgical enterprises. The Pavlodar region, with its concentration of facilities such as the Ekibastuz thermal power plants and the Pavlodar Aluminum Plant, serves as a vivid example of a region where aluminum mobilized in the form of Al^{3+} ions becomes a dominant stress factor for plants, leading to root system suppression, disruption of mineral nutrition, and a decline in ecosystem productivity.

An analysis of 58 scientific sources selected from the Web of Science and Scopus databases for the period 2014-2025 (with reference to foundational works since 1990) has shown that the issue of HM pollution in Kazakhstan remains critical. High levels of lead, cadmium, arsenic, and copper contamination are recorded in industrial centers (Karaganda, Zhezkazgan, Ust-Kamenogorsk), yet it is the secondary aluminum contamination in acidic soils ($pH < 4.5$) that requires special attention and the adaptation of monitoring methods.

Standard methods for analyzing the aerial parts of plants are not informative for assessing aluminum's impact, since more than 95% of Al is accumulated in the root system. The most effective approaches include:

- soil monitoring: determining exchangeable aluminum (extraction with 1M KCl) and soil pH;
- fine root analysis: using highly sensitive methods such as ICP-MS to determine Al content;
- speciation analysis: applying XAFS (X-ray Absorption Fine Structure) methods to identify aluminum's chemical forms and bioavailability.

The unique toxicity mechanism of aluminum—root growth inhibition, cytoskeleton disruption, oxidative stress induction, and impaired uptake of Ca^{2+} and Mg^{2+}—necessitates the development of specific mitigation measures tailored to Kazakhstan:

- application of soil amendments: liming (2-4 t/ha) and addition of organic amendments (biochar, compost) to increase pH and immobilize Al^{3+};
- selection of tolerant species: for landscaping and reforestation in industrial regions, it is essential to use species tolerant to aluminum and acidic soils;
- improved monitoring systems: integrating modern analytical techniques (ICP-MS, XAFS) with traditional biological assessment methods (visual evaluation of root damage, chlorosis).

Thus, a comprehensive approach that combines the reduction of primary SO_2/NO_x emissions, active remediation of acidic soils, and the implementation of an adapted phytomonitoring system is essential to reduce environmental stress and maintain the productivity of agro- and natural ecosystems in industrial regions of Kazakhstan such as the Pavlodar region. Future research should focus on a detailed study of the tolerance mechanisms of local plant species to aluminum, the development of regional standards for mobile forms of Al in soils, and the assessment of the effectiveness of various reclamation practices under the conditions of specific industrial hubs in the country.

Conflict of Interest

Authors declare no conflict of interest.

Author contribution

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. CRediT: **Kaverina M.M. —** investigation, methodology, writing-review & editing; **Ualiyeva R.M. —** conceptualization, data curation; **Syso A.I. —** investigation, literature review, data collection.

References

1 Vareda, J.P., Valente, A.J.M., & Durães, L. (2019). Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: A review. *J. Environ. Manage*, 246, 101–118. https://doi.org/10.1016/j.jenvman.2019.05.126

2 Tseshkovskaya, Y.A., Golubeva, E.I., Ibrayev, M.K., Oralova, A.T., Tsoy, N.K., & Issabayeva, M.B. (2019). Technogenic impact of mining industry on environment in Karaganda region of republic of Kazakhstan. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 6*(438), 85–95. https://doi.org/10.32014/2019.2518-170X.159

3 Singh, R., Gautam, N., Mishra, A., & Gupta, R. (2011). Heavy metals and living systems: An overview. *Indian Journal of Pharmacology, 43*(3), 246–253. https://doi.org/10.4103/0253-7613.81505

4 Information bulletin on the state of the environment of the Republic of Kazakhstan. 1st half of 2024. Astana, 2024; 4-5. Retrieved from https://ecogosfond.kz/orhusskaja-konvencija/dostup-k-jekologicheskoj-informacii/jekologijaly-zha-daj/orsha-an-otrany-zhaj-k-ji-turaly-a-paratty-bjulletender/

5 Sushkova, S., Minkina, T., Dudnikova, T., Barbashev, A., Popov, Y., Rajput, V., Bauer, T., Nazarenko, O., & Kızılkaya, R. (2021). Reduced plant uptake of PAHs from soil amended with sunflower husk biochar. *Eurasian Journal of Soil Science*, *10*(4), 269–277. https://doi.org/10.18393/ejss.935397

6 Zhyrgalova, A., Yelemessov, S., Ablaikhan, B., Aitkhozhayeva, G., & Zhildikbayeva, A. (2024). Assessment of potential ecological risk of heavy metal contamination of agricultural soils in Kazakhstan. *Brazilian Journal of Biology,* 84. https://doi.org/10.1590/1519-6984.280583

7 Shomanova, Z., Nossenko, Y., Yerkibayeva, M., Yessimova, D., Kuspanova, A., Aldasheva, A., Kaimuldinova, K., & Safarov, R. (2025). Environmental risk assessment for sustainable industrial urban development: The case of northern industrial zone of Pavlodar, Kazakhstan. *PLoS ONE*, *20*(4), e0320835. https://doi.org/10.1371/journal.pone.0320835

8 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. *Front Pharmacol*, 13, 12, 643972. https://doi.org/10.3389/fphar.2021.643972

9 Faurat, A., Azhayev, G., Shupshibayev, K., Akhmetov, K., Boribay, E., & Abylkhassanov, T. (2024). Assessment of heavy metal contamination and health risks in "snow cover-soil cover-vegetation system" of urban and rural gardens of an industrial city in Kazakhstan. *International Journal of Environmental Research and Public Health*, *21*(8), 1002. https://doi.org/10.3390/ijerph21081002

10 Kerimray, A., Assanov, D., Kenessov, B., & Karaca, F. (2020). Trends and health impacts of major urban air pollutants in Kazakhstan. *J. Air. Waste Manag. Assoc.*, *70*(11), 1148–1164. https://doi.org/10.1080/10962247.2020.1813837.

11 National report on the state of the environment and the use of natural resources of the Republic of Kazakhstan for 2022. Astana, 2023; 9-10. Retrieved from https://ecogosfond.kz/orhusskaja-konvencija/dostup-k-jekologicheskoj-informacii/jekologijaly-zha-daj/orsha-an-otrany-zhaj-k-ji-turaly-a-paratty-bjulletender/

12 National report on the state of the environment and the use of natural resources of the Republic of Kazakhstan for 2022. Astana, 2023; 10-11. Retrieved from https://ecogosfond.kz/orhusskaja-konvencija/dostup-k-jekologicheskoj-informacii/jekologijaly-zha-daj/orsha-an-otrany-zhaj-k-ji-turaly-a-paratty-bjulletender/

13 Order of the Minister of Health of the Republic of Kazakhstan dated August 2, 2022 No. KR DSM-70 "On approval of Hygienic standards for atmospheric air in urban and rural settlements, on the territories of industrial organizations". Retrieved from https://adilet.zan.kz/rus/docs/V2200029011

14 Beisenova, R., Kuanyshevich, B.Z., Turlybekova, G., Yelikbayev, B., Kakabayev, A.A., Shamshedenova, S., & Nugmanov, A. (2023). Assessment of atmospheric air quality in the region of Central Kazakhstan and Astana. *Atmosphere*, *14*(11), 1601. https://doi.org/10.3390/atmos14111601

15 Li, H., He, Q., & Liu, X. (2020). Identification of long-range transport pathways and potential source regions of pm2.5 and pm10 at akedala station, central asia. *Atmosphere*, *11*(11). https://doi.org/10.3390/atmos11111183

16 Wondimu, T. & Forbes, Patricia. (2015). Metal and metalloid speciation in plants: Overview, instrumentation, approaches and commonly assessed elements. *TrAC Trends in Analytical Chemistry*, 77. 10.1016/j.trac.2015.10.007.

17 He, C., Clifton, O., Felker-Quinn, E., Ryan Fulgham, S., JuncosaCalahorrano, J.F., Lombardozzi, D., … Steiner, A.L. (2021, March 1). Interactions between air pollution and terrestrial ecosystems perspectives on challenges and future directions. Bulletin of the American Meteorological Society. *American Meteorological Society*. https://doi.org/10.1175/BAMS-D-20-0066.1

18 He, S., Niu, Y., Xing, L., Liang, Z., Song, X., Ding, M., & Huang, W. (2024) Research progress of the detection and analysis methods of heavy metals in plants. *Front. Plant Sci.*, *15*, 1310328. https://doi.org/10.3389/fpls.2024.1310328

19 Fuhrer, J., & Bungener, P. (1999). Effects of air pollutants on plants. *Analusis. John Wiley and Sons Inc., 27*(4), 355–362. https://doi.org/10.1051/analusis:1999270355

20 Cronin, P., Ryan, F., & Coughan, M. (2008). Undertaking a literature review: A step-by-step approach. *British Journal of Nursing, 17*(1), 38–43

21 Timothy, N., & Tagui, W.E. (2019). Environmental Pollution by Heavy Metal: An Overview. *International Journal of Environmental Chemistry, 3*(2), 72. https://doi.org/10.11648/j.ijec.20190302.14

22 Saikia, A., & Thapa, P. (2022). Environmental Change in South Asia. *Springer International Publishing*, 8, 233 https://doi.org/10.1007/978-3-030-47660-1

23 Vongdala, N., Tran, H.D., Xuan, T.D., Teschke, R., & Khanh, T.D. (2019). Heavy metal accumulation in water, soil, and plants of municipal solid waste landfill in Vientiane, Laos. *International Journal of Environmental Research and Public Health*, *16*(1), 22. https://doi.org/10.3390/ijerph16010022

24 Alimbaev, T., Mazhitova, Z., Beksultanova, C., & Tentigulkyzy, N. (2020). Activities of mining and metallurgical industry enterprises of the Republic of Kazakhstan: Environmental problems and possible solutions. *In E3S Web of Conferences*. *EDP Sciences*, 175. https://doi.org/10.1051/e3sconf/202017514019

25 Mukhamedzhanov, M.A., Kazanbayeva, L.M., Nurgaziyeva, A.A., & Rakhmetov, I.K. (2019). Environmental problems of south kazakhstan and pollution of drinking groundwater. In *International Multidisciplinary Scientific GeoConference: Surveying Geology and Mining Ecology Management, SGEM*, 19, 207–214. https://doi.org/10.5593/sgem2019/1.2/S02.027

26 Kalimoldina, L.M., Sultangazieva, G.S., & Suleimenova, M.Sh. (2022). Contamination of soils with heavy metal in the urban area of Almaty. *Soil science and agrochemistry*, 3, 38–45. https://cyberleninka.ru/article/n/contamination-of-soils-with-heavy-metal-in-the-urban-area-of-almaty

27 Zhyrgalova, A., Yelemessova, S., Ablaikhana, B., Aitkhozhayeva, G., & Zhildikbayeva, A. (2024). Assessment of potential ecological risk of heavy metal contamination of agricultural soils in Kazakhstan. *Braz. J. Bio.l*, *84*, e280583. https://doi.org/10.1590/1519-6984.280583

28 Matveyeva, I.V., Ponomarenko, O.I., Soltangaziyev, N.B., Nursapina, N.A., Nazarkulova, Sh.N., & Gurin, A.N. (2019). Heavy metals in soils of Almaty region (Kazakhstan). *Chemical journal of Kazakhstan*, *2*(66), 62–68.

29 Tazitdinova, R.M., Beisenova, R.R., Grigoryev, A.I., & Issayenko, O.P. (2019). Contamination of soil with heavy metals in industrial districts of Kokshetau. *Bulletin of the Karaganda university. Biology. Medicine. Geography series*, *2*(94), 93–98.

30 Kocjan, A., Kwasniewska, J., & Szurman-Zubrzycka, M. (2025). Understanding plant tolerance to aluminum: Exploring mechanisms and perspectives. *Plant and Soil*, *507*, 195–219. https://doi.org/10.1007/s11104-024-06745-0

31 Ofoe, R., Thomas, R.H., Asiedu, S.K., Wang-Pruski, G., Fofana, B., & Abbey, L. (2023). Aluminum in plant: Benefits, toxicity and tolerance mechanisms. *Frontiers in Plant Science*, 13, 1085998. https://doi.org/10.3389/fpls.2022.1085998

32 Kochian, L.V., Piñeros, M.A., Liu, J., & Magalhaes, J.V. (2015). Plant adaptation to acid soils: The molecular basis for crop aluminum resistance. *Annual Review of Plant Biology*, *66*, 571–598.

33 Islam, F., Yasmeen, T., Ali, Q., Ali, S., Arif, M.S., Hussain, S. et al. (2014). Influence of Pseudomonas aeruginosa as PGPR on oxidative stress tolerance in wheat under Zn stress. *Ecotoxicol Environ. Saf.*, 104, 285–293. https://doi.org/10.1016/j.ecoenv.2014.03.008

34 Ahammed, G.J., Wu, M.-J., Wang, Y.-Q., Yan, Y.-R., Mao, Q. Ren, J.-J. et al. (2020). Melatonin alleviates iron stress by improving iron homeostasis, antioxidant defense and secondary metabolism in cucumber. *Sci. Hortic.*, 265, 109205. https://doi.org/10.1016/j.scienta.2020.109205

35 Rahman, S.U., Nawaz, M.F., Gul, S., Yasin, G., Hussain, B., Li, Y.-L. et al. (2022). State-of-the-art OMICS strategies against toxic effects of heavy metals in plants: A review. *Ecotoxicol Environ. Saf.*, 242, 113952. https://doi.org/10.1016/j.ecoenv.2022.113952

36 El-Jaoual, T., & Cox, D.A. (1998). Manganese toxicity in plants. *J. Plant Nutr.*, *21*(2), 353–386. https://doi.org/10.1080/01904169809365409

37 Kaur, H., & Garg, N. (2021). Zinc toxicity in plants: a review. *Planta*. Springer Science and Business Media Deutschland GmbH, 253. https://doi.org/10.1007/s00425-021-03642-z

38 Li, G., Kronzucker, H.J., & Shi, W. (2016). The response of the root apex in plant adaptation to iron heterogeneity in soil. Frontiers in Plant Science. *Frontiers Media S.A.*, 7, 344. https://doi.org/10.3389/fpls.2016.00344

39 Veliksar, S., Lemanova, N., Gladei, M., & David, T. (2019). The Impact of Trace Elements Applied with PGPB on the *Vitis vinifera* L Seedlings Resistance to the Copper Excess in Soil. *International Journal of Agriculture and Environmental Science*, *6*(4), 43–47. https://doi.org/10.14445/23942568/ijaes-v6i4p108

40 Ahmed, S., Sameen, & Sardar, R. (2023). Improvement in growth and physiochemical attributes of Raphanus sativus L. through exogenous application of 28-Homobrassinolide under nickel stress. *Sci. Hortic.*, 311, 111791. https://doi.org/10.1016/j.scienta.2022.111791

41 Shetty, R., Vidya, C.S.-N., Prakash, N.B., Lux, A., & Vaculík, M. (2021). Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. *Sci. Total Environ.*, 765, 142744. https://doi.org/10.1016/j.scitotenv.2020.142744

42 Zulfiqar, U., Farooq, M., Hussain, S., Maqsood, M., Hussain, M., Ishfaq, M. et al. (2019). Lead toxicity in plants: Impacts and remediation. *J. Environ. Manage*, 250, 109557. https://doi.org/10.1016/j.jenvman.2019.109557

43 Banerjee, S., Islam, J., Mondal, S., Saha, A., Saha, B., & Sen, A. (2023). Proactive attenuation of arsenic-stress by nanopriming: Zinc Oxide Nanoparticles in *Vigna mungo* (L.) Hepper trigger antioxidant defense response and reduce root-shoot arsenic translocation. *J. Hazard Mater.*, 446, 130735. https://doi.org/10.1016/j.jhazmat.2023.130735

44 Haider, F.U., Liqun, C., Coulter, J.A., Cheema, S.A., Wu, J., Zhang, R., & Farooq, M. (2021). Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicology and Environmental Safety*, 211, 111887. https://doi.org/10.1016/j.ecoenv.2020.111887

45 Ali, S., Mir, R. A., Tyagi, A., Manzar, N., Kashyap, A.S., Mushtaq, M. et al. (2023). Chromium toxicity in plants: signaling, mitigation, and future perspectives. *Plants*, *12* (7), 1502. https://doi.org/10.3390/plants12071502

46 Azevedo, R., Rodriguez, E., Mendes, R.J., Mariz-Ponte, N., Sario, S., Lopes, J.C., … Santos, C. (2018). Inorganic Hg toxicity in plants: A comparison of different genotoxic parameters. *Plant Physiology and Biochemistry*, 125, 247–254. https://doi.org/10.1016/j.plaphy.2018.02.015

47 Kiran, B.R., & Sharma, R. (2022). Effect of heavy metals: An overview. *Materials Today: Proc.,* 51, 880–885. https://doi.org/10.1016/j.matpr.2021.06.278

48 Liang, J., Fang, H.-L., Zhang, T.-L., Wang, X.-X., & Liu, Y.-D. (2017). Heavy metal in leaves of twelve plant species from seven different areas in Shanghai, China. *Urban For Urban Gree,* 27, 390–398. https://doi.org/10.1016/j.ufug.2017.03.006

49 Shahid, M., Dumat, C., Khalid, S., Schreck, E., Xiong, T.-T., & Niazi, N. K. (2017). Foliar heavy metal uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. *J. Hazard Mater.*, 325, 36–58. https://doi.org/10.1016/j.jhazmat.2016.11.063

50 Vetchinnikova, L.V., Kuznetsova, T.Yu., & Titov, A.F. (2013). Features of the accumulation of heavy metals in the leaves of woody plants in urban areas in the North. *Proceedings of the Karelian Scientific Center of the Russian Academy of Sciences*, 3, 68–73.

51 Hrotkó, K., Gyeviki, M., Sütöriné, D.M., Magyar, L., Mészáros, R., Honfi, P., & Kardos, L. (2021). Foliar dust and heavy metal deposit on leaves of urban trees in Budapest (Hungary). *Environmental Geochemistry and Health*, *43*(5), 1927–1940. https://doi.org/10.1007/s10653-020-00769-y

52 Ghuge, S.A., Nikalje, G.C., Kadam, U.S., Suprasanna, P., & Hong, J.-C. (2023). Comprehensive mechanisms of heavy metal toxicity in plants, detoxification, and remediation. *J. Hazard Mater.,* 450, 131039. https://doi.org/10.1016/j.jhazmat.2023.131039

53 Souri, Z., Karimi, N., & Sandalio, L. M. (2017). Arsenic hyperaccumulation strategies: an overview. *Front. Cell Dev. Biol.,* 5. https://doi.org/10.3389/fcell.2017.00067

54 Zhang, D.-Y., Yang, S.-W., Ma, Q.-F., Sun, J.-N., Cheng, H.-Y., Wang, Y.-C. et al. (2020). Simultaneous multi-elemental speciation of As, Hg and Pb by inductively coupled plasma mass spectrometry interfaced with high-performance liquid chromatography. *Food Chem.*, 313, 126119. https://doi.org/10.1016/j.foodchem.2019.126119

55 El-Khatib, A.A., Youssef, N.A., Barakat, N.A., & Samir, N.A. (2020). Responses of Eucalyptus globulus and Ficus nitida to different potential of heavy metal air pollution. *International Journal of Phytoremediation*, *22*(10), 986–999. https://doi.org/10.1080/15226514.2020.1719031

56 Salt, D.E., Blaylock, M., Kumar, N.P.B.A., Dushenkov, V., Ensley, B.D., Chet, I., & Raskin, I. (1995). Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. *Bio/Technology*, *13*(5), 468–474. https://doi.org/10.1038/nbt0595-468

57 Wei, Z., Van Le, Q., Peng, W., Yang, Y., Yang, H., Gu, H., & Sonne, C. (2021). A review on phytoremediation of contaminants in air, water and soil. *Journal of Hazardous Materials*, *403*. https://doi.org/10.1016/j.jhazmat.2020.123658

58 Guo, C.-Y., Lv, L.-J., Liu, Y.-C., Ji, M.-Y., Zang, E.-H., Liu, Q. et al. (2023). Applied analytical methods for detecting heavy metals in medicinal plants. *Crit. Rev. Anal. Chem*., *53*(2), 339–359. https://doi.org/10.1080/10408347.2021.1953371

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Ауыр металдардың өсімдік организмдеріне әсері және оларды талдау әдістері: шолу

Шолу Қазақстанның өнеркәсіптік өңірлеріндегі алюминий уыттылығының бірегей мәселесіне ерекше назар аудара отырып, ауыр металдардың өсімдіктерге әсерін кешенді талдауға арналған. Тау-кен және металлургия салаларының қарқынды дамуы ластаушы заттардың едәуір көлемде шығарылуына әкелуде, олардың ішінде алюминий айрықша экологиялық қауіп тудырады. Басқа металдардан айырмашылығы, оның жоғары фитоуыттылығы жанама түрде — қышқыл жаңбырлардың (SO_2 және NO_x шығарындыларының) топырақты қышқылдандыруы арқылы байқалады. Бұл өз кезегінде табиғи алюмосиликаттардан жоғары уытты Al^{3+} иондарының босап шығуына себеп болады. Павлодар облысының мысалында қайталама алюминиймен ластану парадигмасы мен оның өсімдіктердің тамыр жүйесіне әсер етуінің негізгі механизмдері жан-жақты талданған. Оларға өсу процесінің тежелуі, цитоскелеттің бұзылуы, минералдық қоректенудің бұзылуы және тотығу стресінің индукциясы жатады. Шолуда Қазақстанның түрлі өңірлеріндегі өсімдіктерде ауыр металдардың жинақталуы бойынша заманауи деректер жүйеленіп, алюминийдің биожетімділігі мен уыттылығын дәл бағалау үшін қажетті озық аналитикалық әдістерге (ICP-MS, XAS, EXAFS) сыни талдау жасалған. Өсімдіктердің биоиндикатор ретіндегі рөліне және фиторемедиация әдістерін қолдану мүмкіндіктеріне ерекше назар аударылды. Әдебиеттерге шолу негізінде Қазақстан үшін нақты бейімделу шараларын әзірлеу қажеттігі айқындалады. Оларға топырақты әктеу, көгалдандыру үшін алюминийге төзімді өсімдік түрлерін іріктеу және экологиялық тәуекелдерді азайту мен экожүйелердің өнімділігін сақтау мақсатында заманауи экологиялық мониторинг әдістерін енгізу жатады.

Кілт сөздер: ауыр металдар, алюминий, фитоуыттылық, өнеркәсіптік ластану, қышқыл топырақ, экологиялық бақылау, биожетімділігі, фиторемедиация

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Влияние тяжелых металлов на растительные организмы и методы их анализа: обзор

Данный обзор посвящен комплексному анализу воздействия тяжелых металлов на растительные организмы, с особым фокусом на уникальную проблему токсичности алюминия в промышленных регионах Казахстана. Интенсивное развитие горнодобывающей и металлургической отраслей приводит к значительным выбросам загрязняющих веществ, среди которых особую экологическую угрозу представляет именно алюминий. В отличие от других металлов, его высокая фитотоксичность проявляется опосредованно через подкисление почв кислотными дождями (обусловленными выбросами SO_2 и NO_x), что приводит к мобилизации высокотоксичных ионов Al^{3+} из природных алюмосиликатов. На примере Павлодарской области детально разбирается парадигма вторичного алюминиевого загрязнения, его ключевые механизмы воздействия на корневые системы растений, включая ингибирование роста, разрушение цитоскелета, нарушение минерального питания и индукцию окислительного стресса. В обзоре систематизированы современные данные о накоплении тяжелых металлов в растениях различных регионов Казахстана и критически оценены передовые аналитические методы (ICP-MS, XAS, EXAFS), подчеркивается необходимость специализированного анализа для точной оценки биодоступности и токсичности алюминия. Особое внимание уделено роли растений как биоиндикаторов и перспективам применения методов фиторемедиации. На основе анализа литературы делается вывод о необходимости разработки целевых адаптивных мер для Казахстана, включая известкование почв, подбор алюминий-толерантных видов для озеленения и интеграцию современных методов экологического мониторинга для снижения экологических рисков и сохранения продуктивности экосистем.

Ключевые слова: тяжелые металлы, алюминий, фитотоксичность, промышленное загрязнение, кислотные почвы, экологический мониторинг, биодоступность, фиторемедиация

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