Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Biogeochemical migration of heavy metals in the soil-plant system of Taraz, Kazakhstan: Effects of phosphorus plant emissions

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ABSTRACT
The article discusses the effects of emissions from the Taraz phosphorus plant on soil and vegetation. Analytical data showed that the soils of the investigated sites around the "Kazphosphate" plants, located at various distances from the main plant chimneys, are contaminated with mobile and total forms of zinc, cadmium, and copper. The contamination occurs to a depth of 0–30 cm in all directions according to the wind rose. These elements are the main soil pollutants. According to granulometric indicators, the soil is generally light in texture—sandy, loamy sand, and light loam. In these areas, there is a possibility of heavy metals leaching downward and entering groundwater, posing a threat to the surrounding ecosystem, including humans. Research results showed that the zinc and copper levels in plants were below hazardous thresholds. However, the cadmium and lead levels were several times higher than permissible limits, especially cadmium in the western direction and lead in all directions, particularly east and south. These zones require soil and plant heavy metal monitoring and bioremediation measures.

Keywords: Dominant pollutants, Heavy metals, Monitoring, Soil.
Article type: Research Article.

INTRODUCTION
The industrial extraction and processing of polymetallic ores inevitably lead to significant contamination of the environment with toxic pollutants. The waste of mining and processing enterprises mainly consists of heavy metals entering the biosphere in the form of dust, smoke emissions, and wastewater discharges. The pollution from such enterprises is localized, but the concentration of toxic elements especially heavy metals is quite high. Soil acts as the main medium for heavy metals entering from the atmosphere and water bodies. It serves as a natural buffer that regulates the migration of metals and their compounds to the atmosphere, hydrosphere, and living organisms, thus becoming a long-term source of secondary pollution (Perelman & Kasimov 2000;

Caspian Journal of Environmental Sciences, Vol. 23 No. 4 pp. 871-883 Received: Jan. 14, 2025 Revised: May. 08, 2025 Accepted: June 23, 2025
DOI: 10.22124/cjes.2025.9204

Publisher: University of Guilan,

Dzhuvelikyan *et al.* 2009). The persistence of contaminants in soil is significantly longer compared to other parts of the biosphere, especially in the case of heavy metals (Tivo & Bytsko 1996; Korelskiy 2008). The issue of soil contamination remains even after industrial operations cease. Metals accumulate in soil and are removed slowly via leaching, plant uptake, erosion, and deflation (Kabata-Pendias & Pendias 1989). The half-life of heavy metals varies greatly: for Zn – 70 to 510 years; Cd – 13 to 110 years; Cu – 310 to 1500 years; Pb – 740 to 5900 years (Alekseev 1987). Heavy metals have surpassed pesticides and even well-known pollutants like the carbon and sulfur dioxide in terms of hazard level, ranking second among the most dangerous environmental contaminants. In the future, they may pose greater risks than even nuclear waste (Filov 1988). The increase in heavy metal content not only disrupts ecological balance but also causes severe human health issues. Soil, vegetation, and water contamination with heavy metals around major industrial centers has become one of the most pressing environmental problems. Each year, metallurgical enterprises release at least 154,650 tons of copper, 89,000 tons of lead, 121,500 tons of zinc, 12,000 tons of nickel, 765 tons of cobalt, 1,500 tons of molybdenum, and 30.5 tons of mercury into the environment. A preliminary study of Kazakhstan's land resources has revealed significant contamination of soils with toxic chemicals and heavy metals, resulting in a rapid decline in fertility (Omarkulov 1994). According to data from various authors, the total area in Kazakhstan affected by industrial atmospheric emissions is 1.58 million hectares, of which 780 thousand hectares are agricultural lands. High concentrations of heavy metals in soil have a corresponding effect on plant products grown within the industrial zones. Many garden crops show heavy metal content exceeding the allowable concentration by 2 to 3.5 times (Vazhenina & Fateeva 1987; Chernykh 1991). Due to the importance of Southern and Southeastern Kazakhstan for agricultural production, the regions around cities such as Taraz, Shymkent, Tekeli, and Taldykorgan, along with other major industrial settlements, have developed geochemical provinces with excessive accumulation of pollutants. In these areas, the dominant soil pollutants include lead, zinc, cadmium, fluoride, and toxic salts. More than 40% of vineyard plantations in Southern Kazakhstan grow on lands with excessive boron and soluble salts. One of the key factors in the instability and imbalance of agro-landscapes is the technogenic contamination of agricultural land. Ignoring the resource potential and operating modes of agro-ecosystems under increasing technogenic pressure intensifies negative processes, leading to contamination with chemicals, including fertilizers and pesticides. The intensification of agricultural technologies often has undesirable consequences: chemical compositions of air, water, soil, and organisms change, and ecological links in the agro-landscape are disrupted. Additionally, the presence of ballast elements, including heavy metals, in mineral fertilizers contributes to agro-landscape contamination. To restore soil fertility through organic and mineral fertilization, continuous input of substances and energy is necessary. The application of nutrients—especially organic fertilizers—is a key method to enhance soil fertility (Artyushin *et al.* 1991). Disruption of nutrient balance in agro-landscapes ultimately leads to significant deviations in agrocenosis productivity and the state of the surrounding environment. The inconsistency and violations of environmental safety standards regarding fertilizers and pesticides lead to not only ecological but also economic problems, reducing agricultural efficiency (Bondina & Nezvankina 2006). Given the potential hazard of soil contamination with chemicals, quality control and dosage regulation of fertilizers must consider soil agrochemical properties and plant nutrient requirements across different types of agro-landscapes (Mikhaleva 1997). Thus, the strategy of developing fertilizer systems in agro-landscapes must be both ecologically and economically justified, aiming to ensure an optimal balance of humus and mineral substances while adhering to environmental protection standards. Due to their high toxicity and accumulation potential, contamination with heavy metals and radionuclides is the most serious form of pollution. Heavy metals entering soil from the atmosphere or through wastewater not only pollute it but also hinder natural soil formation processes. Sources of heavy metal and pollutant input include both natural and anthropogenic processes. Natural sources include water erosion and the weathering of rocks and minerals. Anthropogenic sources include aerosols, dust, industrial discharges, domestic waste, livestock waste, pesticides, organic and mineral fertilizers. Areas near large industrial enterprises and major transportation routes are the most contaminated. Emissions from industry and transport extend into adjacent territories, contaminating agricultural products (Artyushin *et al.* 1991; Mikhaleva 1997; Bondina & Nezvankina 2006). According to Hydromet data, due to wind direction, Taraz city's atmosphere is polluted with sulfur dioxide. The main contributors to air pollution are the phosphorus industry enterprises "Khimprom" chemical production association, the new phosphorus plant, and the superphosphate plant. Phosphogypsum waste piles are located near Taraz. These act as contamination sources through water and wind erosion, chemical leaching, and fluctuating redox conditions. For every ton of phosphogypsum, the mobile forms of contaminants entering soil in plant-available forms include: 700 g strontium, 110 g iron, 55 g yttrium, 30 g cerium, 12 g chromium, 11 g titanium, 5 g zinc, 4 g each copper and lead, 3 g each vanadium and cadmium, 2 g each arsenic and nickel, and 1 g uranium (Moroz 2000). These phosphogypsum dumps are major sources of the soil, plant, and air pollution. Undoubtedly, the phosphorus plant in Zhambyl region and its emissions pose an ecological threat to agricultural soils, crops, and local populations. However, there is currently no effective monitoring of heavy metal contamination in soils used for agriculture. The presented materials on the soil-ecological status of agro-landscapes and areas affected by emissions from mining and phosphorus industries demonstrate the relevance of this research. It holds significant scientific and practical value in developing a sustainable agro-industrial complex and ensuring food security in Kazakhstan.

MATERIALS AND METHODS

Research object. The soil-plant system of areas contaminated by emissions from the phosphorus plant located in the Zhambyl district of Taraz City, Zhambyl region. The study was conducted in the Zhambyl district, where the phosphorus plant is located (Fig. 1). The terrain is diverse, with most of the area covered by the Karatau Mountains and the Kyrgyz Range; the central part is elevated, while the northern part is flat. The subsoil contains reserves of natural construction materials. The region has a continental climate with mild winters and hot summers. The average temperature in January is -6 to -7 °C, and in July, 22-26 °C. The average annual precipitation ranges from 250 to 400 mm. The Talas and Asy rivers flow through the district. Lakes include Bögetköl, Suluköl, Sengirbay, Kökis, and others.

Soil types. Mountain-meadow, mountain-steppe, gray soils, meadow-gray soils, and meadow-swamp soils.

Fig. 1. Study site in Zhambyl District, Zhambyl Region.

Research Methods. This study applied an integrated ecosystem-based approach combining field surveys, experimental monitoring, cartographic interpretation, and laboratory analysis to assess soil and vegetation conditions in the vicinity of industrial emissions. Fieldwork included soil pit excavation, morphological description of soil horizons, and systematic sampling for further laboratory examination. Both impacted and background (uncontaminated) soils were analyzed for their physical and chemical characteristics using established soil science procedures.

RESULTS AND DISCUSSION

A preliminary site survey of the study area (Zhambyl district) made it possible to identify key sampling points for collecting soil samples in order to assess the impact of phosphorus plant emissions on surrounding agricultural lands (Fig. 2).

Table 1. General analytical methods.

Parameter / Method	Analytical technique used
Humus content	Tyurin method
Total nitrogen	Kjeldahl digestion
Total phosphorus and potassium	Acid digestion followed by colorimetric or flame photometry
Hydrolyzable nitrogen	Tyurin-Kononova method
Available phosphorus and potassium	Extraction with mild acids and subsequent analysis
Soil pH	Potentiometric method in water suspension
Exchangeable Ca and Mg	Titration after ammonium acetate extraction
Exchangeable K and Na	Flame photometry after ammonium acetate extraction
Particle-size and microaggregate distribution	Pipette method (Kachinsky)

Table 2. Heavy metal determination.

Element	Method for mobile forms	Method for total forms
Copper (Cu)	Extraction with acetate buffer and atomic absorption spectrometry (AAS)	Acid digestion and AAS
Zinc (Zn)	Extraction with acetate buffer and AAS	Microwave digestion and AAS
Lead (Pb)	Nitric acid extraction and AAS	Aqua regia digestion and AAS
Cadmium (Cd)	Nitric acid extraction and AAS	Aqua regia digestion and AAS

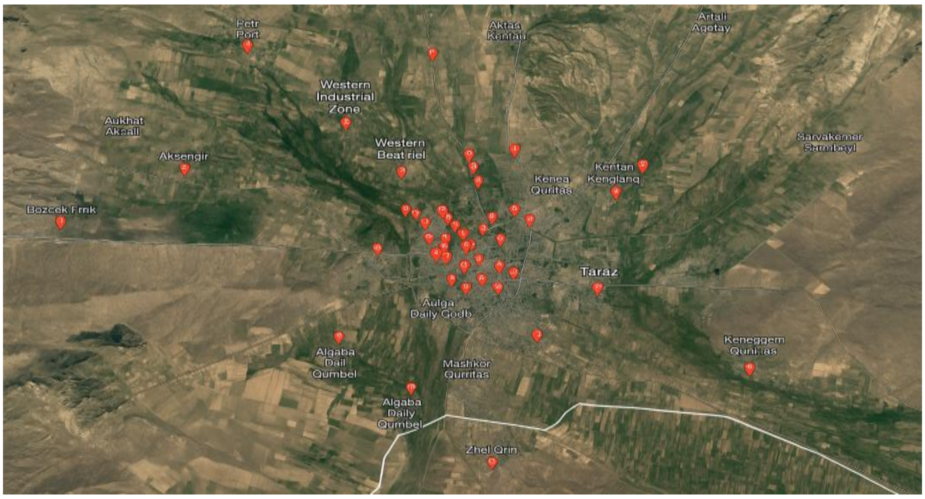

Fig. 2. Map of key soil sampling points to determine the impact of phosphorus plant emissions on surrounding agro-landscapes in Zhambyl district, Zhambyl region.

Morphogenetic description of soil pits. Pit 1: was excavated and described in undisturbed zonal gray soil. The vegetation cover was 100%, including grasses, wormwood, reeds, and other species. Coordinates: 43°00′16.04″ N, 071°25′27.92″.

Elevation. 549 meters above sea level

0–7 cm. Turf, dark gray, dry, slightly compacted, nutty-granular-powdery-dusty, sandy loam, insect larvae and earthworms present, effervesces when HCl is applied; clear transition to the next layer.

7–16 cm. Light gray, varying moisture levels, blocky-nutty-powdery, sandy loam, abundant roots and carbonates, coprolites and earthworms present, effervesces with HCl, clear transition by stratification.

16–31 cm. Light gray with brownish tint, moist, partly dense or slightly compacted, weak blocky-dusty, sandy loam, white powdery carbonates, large and fine reed roots, partially decomposed plant debris, insect burrows present, effervesces with HCl, transition by density and layering is clear.

31–79 cm. Gray-brown, nutty-powdery-dusty, slightly compacted, sandy loam, dense, reed and fine plant roots present, fine porosity, effervesces with HCl, transition by color and layering is distinct.

79–107 cm. Brown-tinted ochre, moist, slightly compacted, nutty-powdery structure, sandy loam, fine porosity, partially decomposed root residues, effervesces with HCl, transition by layering is distinct.

107–120 cm. Light ochre, moist, dense, nutty-powdery, sandy loam, fine plant roots, carbonate mottling present, strong effervescence with HCl.

In Zhambyl district, Soil Pit 1 was dug and morphologically described in a sugar beet field. Soil samples were collected, and the field is located near the "Kazphosphate" plants. Harvesting of sugar beets was underway at the time of the survey. Notably, the irrigation method is by furrows. Depending on their type, the root crops varied in size and weight. Numerous small-sized root crops were observed, growing in close proximity to each other, indicating that no thinning was carried out during the growing season.

Fig. 3. Soil pit 1. **Fig. 4.** Vegetation cover.

Soil Pit 2. Description and environmental context

Pit 2 was excavated and described in a sugar beet field. Sugar beet harvesting was ongoing at the time of sampling. Elevation: 580 m., coordinates: 42º56′40″ N, 71º18′29″ E.

Fig. 5. Pit 2.

0–14 cm. Dark gray, moist, slightly compacted, finely porous, blocky-granular, heavy sandy loam, strong effervescence with HCl, gradual transition to the next layer

14–25 cm. Gray with dark tint, moist, slightly compacted, blocky-granular, heavy sandy loam, earthworms and their coprolites observed, sparse root hairs, presence of large and small gravel fragments, strong effervescence with HCl, gradual transition

25–35 cm. Grayish-brown, moist, compact, blocky-powdery, heavy sandy loam, porous, sparse root hairs, large and small gravel particles, strong effervescence with HCl, gradual transition

35–50 cm. Brown, moist, few root hairs, large and small gravel particles, stony, strong effervescence with HCl, distinct transition

50–80 cm. Brownish-dark, damp, compacted, weak blocky-powdery structure, sandy sandy loam, strong effervescence with HCl

Impact of phosphorus plants on soil pollution

Phosphorus plants emit not only phosphorus compounds but also heavy metals such as cadmium, lead, mercury, and chromium into the atmosphere. These emissions, consisting of gases and fine particles, can settle in soil and plants, leading to contamination far from the source. Depending on meteorological conditions, terrain, and other factors, emissions may disperse over tens of kilometers, and in some cases even further. An increase in heavy metals in the soil due to emissions from phosphorus plants is influenced by the concentration of pollutants in the emissions, the distance from the plant, soil type, and climate conditions. Emissions from phosphorus industries often contain cadmium, lead, zinc, nickel, copper, and fluorine.

Factors affecting the spread of pollution

Distance from the plant. The highest exceedance of maximum permissible concentrations (MPC) is observed within a radius of 1–3 km. Pollution levels decrease by distance but can persist up to 10–15 km.

Weather conditions. Wind, precipitation, and terrain contribute to pollutant dispersion and can cause accumulation in certain areas.
Soil type. Clay and soils rich in organic matter have high sorption capacities, and slowing the leaching of heavy metals. Sandy soils retain less pollution and transfer it more quickly to plants.
Thus, emissions from phosphorus plants may cause heavy metal concentrations in nearby areas to exceed MPCs by several times. This poses risks of toxic accumulation in soils and potential transfer to plants and the food chain. In light-textured soils, pollutants may also infiltrate groundwater.

Contamination Zones according to A.A. Aidosov and N.S. Zaurbekova
Soils with heavy metal concentrations not exceeding 1.5 times the background in the upper layer are considered conditionally clean. Based on this:
For copper, the contamination zone radius is 12–18 km, and 9 km toward the south.
For lead and cadmium, the contamination zone radius is 8–12 km, and 6 km to the south.
The area contaminated by zinc is smaller, with a radius of 6–10 km, and 3 km to the south and southwest.
The most contaminated area is located directly near the plant with a radius of 1–2 km, where:
Lead and cadmium exceed the background levels by 2×,
Zinc: slightly below that,
Copper: by 1×
Metal concentrations drop sharply with distance from pollution sources. The observed technogenic anomalies poorly align with dominant wind directions, likely due to complex wind patterns in the foothills, where easterly and southeasterly winds prevail.
Within the sanitary protection zone of phosphorus enterprises near Taraz, heavy metals in soils exceed background levels (even up to 100 km from the plant):
Lead: 6×
Copper: 3×
Chromium: 3×
Zinc: 37×
Fluorine: 8×
Boron: 8×
Cadmium: 6×
Manganese: 5.6×
Our analytical data allowed the determination of total and mobile forms of heavy metals in the soils of Zhambyl district (see Table 3).
Heavy metals are highly toxic substances that accumulate in the soil as a result of anthropogenic impact. Environmental protection studies pay close attention to the presence of heavy metals in the soil, as their concentrations significantly affect biological conditions—particularly the functioning of the soil microbiota—and the interactions within the "soil–plant" system. These concentrations also influence the state of vegetation in the area and, ultimately, the overall environmental health, including public health. According to the analytical data on the concentrations of total and mobile forms of heavy metals in the soil of the studied area, a slight increase in total zinc content was observed in the upper layers of Soil Pit 1. For instance, in the 0–14 cm layer, the total Zn content exceeded the maximum permissible concentration (MPC = 100) by 1.85 times (or 85.2%), and in the 14–25 cm layer by 1.01 times (or 10.1%). Similarly, the total Cd content (MPC = 5) in the 0–14 cm layer was 1.12 times higher (or 12%), and in the 14–25 cm layer 1.2 times higher (or 20%). A slight increase in total Zn content was also recorded in samples collected from different parts of the agro-landscape. In the profile of the undisturbed zonal soil, the total Cd content in all layers exceeded the MPC by 1.2 to 1.68 times (see Table 1).
In the undisturbed zonal gray soil, the Maximum Permissible Concentration (MPC) for cadmium (Cd) is set at 5%. We calculate how many times the cadmium concentration exceeds the MPC in each soil layer:
0–7 cm: 7.6 / 5 = 1.52 times
7–16 cm: 6.0 / 5 = 1.2 times
16–31 cm: 8.0 / 5 = 1.6 times
31–79 cm: 6.0 / 5 = 1.2 times
79–107 cm: 7.2 / 5 = 1.44 times

107–120 cm: 8.4 / 5 = 1.68 times

Thus, cadmium concentrations in all soil layers exceed the MPC by 1.2 to 1.68 times.

Table 3. Concentration of of total and mobile forms of heavy metals.

Depth (cm)	Mobile forms (mg kg^{-1})				Total forms (%)			
	Zn MPC 23	**Cu MPC 3**	**Cd MPC 2**	**Pb MPC 6**	**Zn MPC 100**	**Cu MPC 55**	**Cd MPC 5**	**Pb MPC 30**
Pit 1-undisturbed zonal gray soil								
0–7	4.4	1.0	1.0	0.4	64.8	24.4	7.6	5.6
7–16	3.8	1.4	1.4	0.4	67.6	24.0	6.0	6.4
16–31	1.9	1.8	1.8	0.3	60.0	23.6	8.0	5.6
31–79	2.4	3.0	3.0	0.5	55.6	26.4	6.0	4.8
79–107	2.3	2.5	2.5	1.3	324.0	23.6	7.2	4.4
107–120	9.7	2.6	2.6	0.9	52.8	22.8	8.4	6.8
Agrolandscape, Zhambyl district, 2-pit, sugar beet								
0–14	1.6	1.8	1.6	1.1	185.2	36.0	5.6	8.4
14–25	1.0	1.7	1.4	0.7	101.6	31.2	6.0	12.0
25–35	1.4	1.6	1.3	0.8	74.4	26.4	2.0	11.2
35–50	1.1	1.9	1.1	1.0	67.2	24.0	4.8	9.6
50–80	1.1	1.1	0.8	1.5	70.4	27.6	3.2	9.2
Point 1. Agrolandscape, Zhambyl district								
0–10	3.1	0.9	1.2	1.3	96.0	32.4	2.4	10.0
10–20	2.0	0.7	1.8	1.8	95.6	32.8	2.8	9.6
20–30	1.4	1.2	2.1	1.4	109.6	36.4	2.4	8.0
Point 2. Agrolandscape, Zhambyl district								
0–10	1.5	1.0	1.9	1.4	104.4	37.2	2.4	8.4
10–20	2.2	1.2	2.3	1.5	85.2	38.4	4.0	7.6
20–30	2.3	1.3	0.5	1.8	95.2	38.8	4.4	7.6
Point3. Agrolandscape, Zhambyl district								
0–10	1.8	1.4	1.0	0.9	82.4	37.6	4.8	8.4
10–20	1.7	1.9	1.0	1.3	84.8	34.0	6.4	8.0
20–30	2.8	1.8	0.7	1.3	90.8	34.4	6.8	6.4
Point 4. Agrolandscape, Zhambyl district								
0–10	3.2	1.6	1.3	1.2	76.0	25.2	4.8	8.0
10–20	3.6	1.7	1.5	0.9	68.0	26.4	5.6	7.6
20–30	4.2	1.4	1.4	1.1	77.6	22.4	4.0	5.2

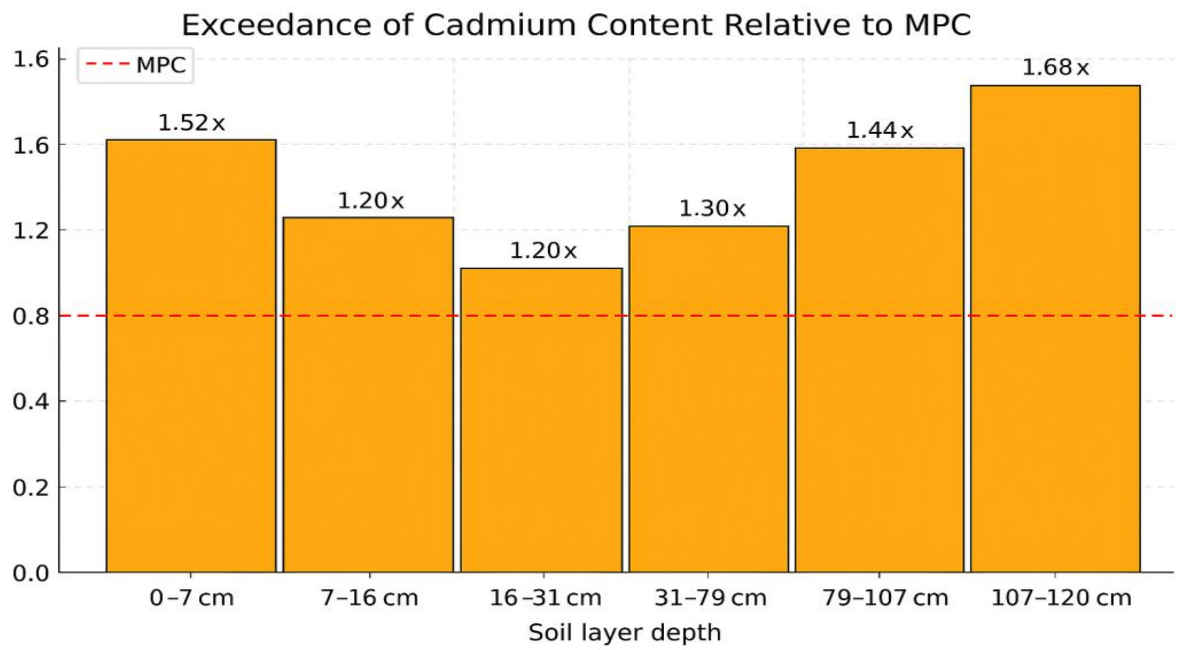

Fig. 6. Total cadmium content in undisturbed zonal gray soil.

According to the data provided by F.E. Kozybayeva *et al.* (Annual Report 2024), the ecological-toxicological assessment of heavy metal content in the soils of the studied agricultural lands shows that 0.83% of the land designated for agriculture is contaminated with category I hazardous substances, and 4.83% with category II hazardous substances (see Table 4).

Table 4. Ecological-toxicological assessment of heavy metal contamination in agricultural soils.

Element	Hazard category	Surveyed area (thousand ha)	Contaminated area (thousand ha)	Share of contaminated soil (%)
Cadmium	I	175800	1459	0.83
Zinc	II	175800	2651	1.51
Copper	II	175800	5843.95	3.32

When analyzing the soil samples taken according to wind directions, cadmium, zinc, and copper were identified as the predominant pollutants. The concentrations of these heavy metals exceed the Maximum Permissible Concentrations (MPCs). Analysis of both total and mobile forms of these trace elements revealed a significant exceedance of MPC levels. The mobile zinc content in the north and northwest directions up to 5 km from the plant exceeds the MPC by 1.1 to 5.0 times. The mobile copper content exceeds the MPC by 1.1 to 2.3 times in the north, northwest, east, and southeast directions up to 10 km from the plant. The mobile cadmium content exceeds the MPC by 1.1 to 1.2 times in the north and northeast directions up to 5 km from the plant. The total zinc content exceeds the MPC by 1.1 to 4.4 times in all directions up to 20 km from the plant. The mobile copper content exceeds the MPC by up to 10 times in the north, south, and southeast directions at distances of 1.1 to 2.7 km from the plant. The total cadmium content exceeds the MPC by 1.1 to 2.6 times in the north, northwest, and west directions up to 20 km from the plant.

Table 5. Maximum exceedance of heavy metals above MPC in soil at the study site.

Metal	Form	MPC (mg kg^{-1})	Max value (mg kg^{-1})	Exceeds MPC (times)	Sampling location (by wind direction)
Zinc (Zn)	Total	100	444.0	4.44	Northwest: 2 km (0–10 cm)
	Mobile	23	114.0	4.96	Northwest: 2 km (0–10 cm)
Copper (Cu)	Total	55	149.6	2.72	Southeast – 10 km
	Mobile	3	6.3	2.1	South: 1 km
Cadmium (Cd)	Total	5	12.8	2.56	Southwest: 20 km
	Mobile	2	3.5	1.75	Northwest: 1 km (10–20 cm)

According to analytical data, the soils of the studied sites around the "Kazphosphate" plants are contaminated by both mobile and total forms of zinc (Zn), cadmium (Cd), and copper (Cu) at varying distances from the main emissions of the factory pipelines. The contamination occurs in the topsoil at depths of 0-30 cm in all wind directions. These elements are the primary pollutants in the soil. The soil is predominantly light in texture based on granulometric indicators, i.e., sandy, sandy loam, and light clay. These areas potentially allow downward migration of heavy metals and their infiltration into groundwater, posing a risk to the surrounding ecosystem, including humans, due to the absence of clayey soils that would otherwise act as a barrier. Plants are the main source of heavy metal entry into the human and animal body. According to various sources, 40 to 80% of heavy metals are absorbed through plants, while only 20-40% are ingested through air and water (cyberleninka.ru › article/n/soderzhanie-tyazhelyh-). Thus, the level of metal accumulation in food crops significantly impacts public health. Environmental pollution, particularly in urban and industrial areas, remains a pressing ecological issue. The effect of toxicants leads to a substantial deterioration in the condition of vegetation. Mitigating the adverse effects of technogenic impact is possible by improving environmental protection measures. Accordingly, the role of ecological monitoring is increasing across various sectors of environmental, economic, and scientific-research activities. Among the components of the biosphere's living matter, plants, especially forest plantations and natural forests, are the most important for absorbing and neutralizing gaseous toxicants (new.u-center.info libraryschoolboy/researchbio/...). Forest ecosystems can process up to 1,000 m^3 of air per day per 500 ha using their assimilation apparatus (studbooks.net › 999214/ecology/rol_zelenyh_...). Fully developed forest stands forming 4 tons of leaves per hectare can absorb about 10 tons of toxic gases during the growing season (cyberleninka.ru › article/n/otsenka-ekologicheskoy-...). The chemical composition of plants reflects the elemental composition of the soil. Therefore, excessive accumulation of heavy metals in plants is primarily due to their high concentrations in the soil (Ilyin 1991). The mechanisms of plant tolerance to excess heavy metals vary: some species accumulate high concentrations of metals but remain tolerant, while others minimize uptake through their barrier functions. For most plants, the root system serves as the first line of defense, where the majority of metals are retained, followed by stems and leaves, and finally the reproductive organs (nsportal.ru, ap/library/nauchno-tekhnicheskoe-...). Another pathway for heavy metal entry into plants is through foliar absorption from the air. This route is especially prevalent near major industrial enterprises, where metals from the atmosphere deposit directly onto foliage. Entry occurs mainly via non-metabolic penetration through the cuticle. Absorbed metals may translocate to other organs and tissues and participate in metabolism (Bayseitova & Sartaeva 2014). The phytotoxic effects of heavy metals become evident under high levels of soil contamination and are influenced by the properties and behavior of specific metals. For instance, cadmium toxicity in plants manifests as disruption of enzyme activity, inhibition of photosynthesis, impaired transpiration, and suppression of NO_2 to NO conversion. Moreover, cadmium acts as an antagonist to several essential nutrients (Zn, Cu, Mn, Ni, Se, Ca, Mg, and P; Pobilat & Voloshin 2017). Excessive lead levels in soil inhibit respiration and photosynthesis in plants, potentially increasing cadmium accumulation and reducing zinc, calcium, phosphorus, and sulfur uptake. Zinc excess occurs mainly in industrially contaminated areas. Although many plant species tolerate high zinc levels, extremely elevated concentrations can cause leaf chlorosis, a typical symptom of zinc toxicity. Zinc excess also antagonizes copper and iron uptake, manifesting in their deficiency symptoms. However, in nature, metal ions rarely exist in isolation. Therefore, various combinations and concentrations of metals in the environment may alter their properties due to synergistic or antagonistic interactions. For example, a mixture of zinc and copper is five times more toxic than the sum of their individual toxicities due to synergy. On the other hand, zinc and cadmium demonstrate physiological antagonism. In complex metal mixtures, both synergism and antagonism are evident. Hence, the cumulative toxicological impact of heavy metals depends not only on their individual concentrations but also on their interactions with biota (Seredina 2015). Pollutants can spread tens of kilometers from their emission sources. Up to 10-30% of airborne metal emissions can disperse more than 10 km from industrial sites. Plants experience mixed contamination due to direct deposition of aerosols and dust on foliage and prolonged root uptake of metals accumulated in soil (Zyrin 1986). Data on anthropogenic activity indicate that 94-97% of lead, 84-89% of cadmium, 56-87% of copper, 66-75% of nickel, and 58% of mercury emissions are technogenic. Of the global anthropogenic metal flow, 26-44% falls on Europe, with 28-42% occurring in the European part of the former USSR (Zyrin 1986; Artamonov 1986). Thus, this material highlights the significant contribution of major cities to the soil and plant contamination with heavy metals. The heavy metal issue and its impact on living organisms have become one of the "acute" problems in modern environmental science.

Emissions from phosphate plants contain several substances that may adversely affect vegetation. Major pollutants include:

Fluorine and its compounds. Common in phosphate emissions, they accumulate in plant leaves and lead to photosynthesis disruption, cell membrane damage, chlorosis, necrosis, stunted growth, and reduced yield.

Dust and particulates. Deposit on leaves, blocking light and reducing photosynthesis. They alter soil composition, affecting nutrient availability.

Heavy metals. Including cadmium, lead, mercury, and others—accumulate in plant tissues, reduce root nutrient and water uptake, and are toxic to soil microflora.

Sulfur and nitrogen compounds. Increase soil acidity, reduce fertility, and cause leaf burns.

Soil chemistry alteration. Phosphorus compounds may disrupt macro- and micronutrient balance. Excess phosphates hinder iron and zinc uptake.

Outcomes of exposure. Stunted growth, reduced fruit quality, increased susceptibility to disease and stress. To mitigate impacts, it is crucial to:

Use protective forest belts;

Conduct soil analysis to detect disruptions;

Increase organic matter content to reduce toxicity. Plants play a key role in the geochemical cycling of chemical elements, including heavy metals. In the "soil-plant" system, mineral flows are formed and transferred to consumers. Hence, understanding heavy metal behavior in this system is critical (Kabata-Pendias 2011). Important factors influencing heavy metal content in plants include the geochemical characteristics and properties of the soil (Kebede *et al.* 2016). In areas with high urbanization, heavy metal accumulation in soil is most intense for Cd, Pb, Cu, and Zn, which require special attention (Misigryan 2006; Titov *et al.* 2014). The concentration of heavy metals in plant organs, especially roots, closely correlates with their levels in the soil. The permissible concentration (MPC) of heavy metals for plants depends on soil content and plant accumulation capacity. MPCs are typically evaluated for food crops since soil is the primary route of metal uptake.

Wind direction and exposure areas. Wind direction plays a key role in emission dispersion. Areas located downwind from the plant are subject to the highest contamination. Emission intensity decreases with distance but may locally accumulate in calm or topographically hindered regions.

Elevated heavy metal concentrations (Zn, Cu, Cd, and Pb) in underground and above-ground parts of plants such as alfalfa, maize, winter wheat, thistle, wormwood, and cereals indicate significant environmental pollution. Key aspects of this issue and potential impacts for each plant are as follows:

Alfalfa (*Medicago sativa*). Above-ground parts: Accumulation in leaves and stems reduces nutritional value. Alfalfa actively absorbs Cd and Zn but accumulates Pb relatively slowly. Roots: Primary site for Pb retention with limited translocation to shoots.

Maize (*Zea mays*). Above-ground parts: Actively absorbs Zn and Cu in leaves and stems. Cd accumulates in grains, posing a food chain risk. Roots: Accumulate more heavy metals, especially Cd and Pb, than aerial parts.

Table 6. Toxic Concentration levels of heavy metals in plants (mg kg^{-1} dry mass).

Metal	Toxic concentration level (mg kg^{-1} dry mass)
Zinc (Zn)	> 100–400
Copper (Cu)	> 20–100
Cadmium (Cd)	> 5–10
Lead (Pb)	> 2–5

Table 5. Total forms of heavy metals in plants (mg kg^{-1}).

Sampling location by wind direction	Plant and its part	Total forms (mg kg^{-1})			
		Zn (MPC 150)	Cu (MPC 15)	Cd (MPC 0.5)	Pb (MPC 0.5)
North – 1 km	Wormwood (*Artemisia*), above-ground	41.8	12	0.4	2.2
	Exceeds MPC by				4.4 times
North – 1 km	Wormwood (*Artemisia*), below-ground	34.2	12.2	0.6	2.4
	Exceeds MPC by			1.2 times	4.8 times
North – 5 km	Maize (Zea mays), above-ground	25.8	7	0.8	2
	Exceeds MPC by			1.6 times	4 times
North – 5 km	Maize (*Zea mays*), below-ground	25.2	9.6	0.6	1.6
	Exceeds MPC by			1.2 times	3.2 times
South–10 km	Bluegrass (*Poa pratensis*), above-ground	22.8	9.2	1.2	1.6
	Exceeds MPC by			2.4 times	3.2 times
South–10 km	Bluegrass (*Poa pratensis*), below-ground	26.6	8.6	1.0	1.8
	Exceeds MPC by			2 times	3.6 times
East – 10 km	Alfalfa (*Medicago*), above-ground	16	10.4	0.4	2
	Exceeds MPC by				4 times
East – 10 km	Alfalfa (*Medicago*), below-ground	23.6	12.4	0.2	3.2
	Exceeds MAC by				6.4 times
West – 2 km	Alfalfa (*Medicago*), above-ground	14.8	9.6	0.2	2
	Exceeds MPC by				4 times
West – 2 km	Alfalfa (*Medicago*), below-ground	18.4	9.4	4.8	2
	Exceeds MPC by			9.6 times	4 times

These concentrations can exert toxic effects on plants, reducing their growth and productivity. Below are the primary effects of elevated heavy metal levels in plant tissues:

Zinc (Zn): At high concentrations, it inhibits root system development and photosynthesis.
Copper (Cu): Toxic to root tissues and can inhibit enzymatic processes.
Cadmium (Cd): One of the most toxic metals; even in small amounts, it disrupts metabolism and reduces photosynthesis.
Lead (Pb): A strong growth inhibitor that accumulates in cell walls and disrupts water exchange.

Brief analysis of heavy metals in plants (Table 5, Fig. 7)

Zinc (Zn): MPC 150 mg kg^{-1}, all samples contain Zn levels below the MPC, Highest concentration: Wormwood (above-ground part), North direction 1 km – 41.8 mg kg^{-1}. Safe levels, though relatively higher concentrations were observed in northern samples.

Copper (Cu): MPC 15 mg kg^{-1}, Cu levels in all samples are below the MPC, indicating permissible and safe values, highest concentration: Alfalfa (underground part), East 10 km – 12.4 mg/kg. These values also do not pose any ecological hazard.

Cadmium (Cd): MPC 0.5 mg kg^{-1}, Cd levels exceed the MPC in several samples, indicating potential ecological risk: Maize (above-ground), North 5 km – 0.8 mg kg^{-1} (1.6 times the MPC); Bluegrass (above-ground), South 10 km – 1.2 mg kg^{-1} (2.4 times the MPC); Alfalfa (underground), West 2 km – 4.8 mg/kg (9.6 times the MPC);
In conclusion: Cd contamination is particularly evident in the western direction.

Lead (Pb): MPC 0.5 mg kg^{-1}, all samples contain Pb concentrations significantly above the MPC, indicating ecological danger: Alfalfa (underground), East 10 km – 3.2 mg kg^{-1} (6.4 times the MPC); Bluegrass (underground), South 10 km – 1.8 mg kg^{-1} (3.6 times the MPC). In conclusion: Pb is the most exceeded heavy metal. The exceedance is observed in all directions.

Zn and Cu: Overall conclusion: Below hazardous levels – considered safe. Cd and Pb: Exceed the MPC by several times, especially Cd in the western direction Pb in all directions, notably in eastern and southern samples. These areas require regular monitoring and implementation of bioremediation strategies to mitigate heavy metal accumulation in soils and plants.

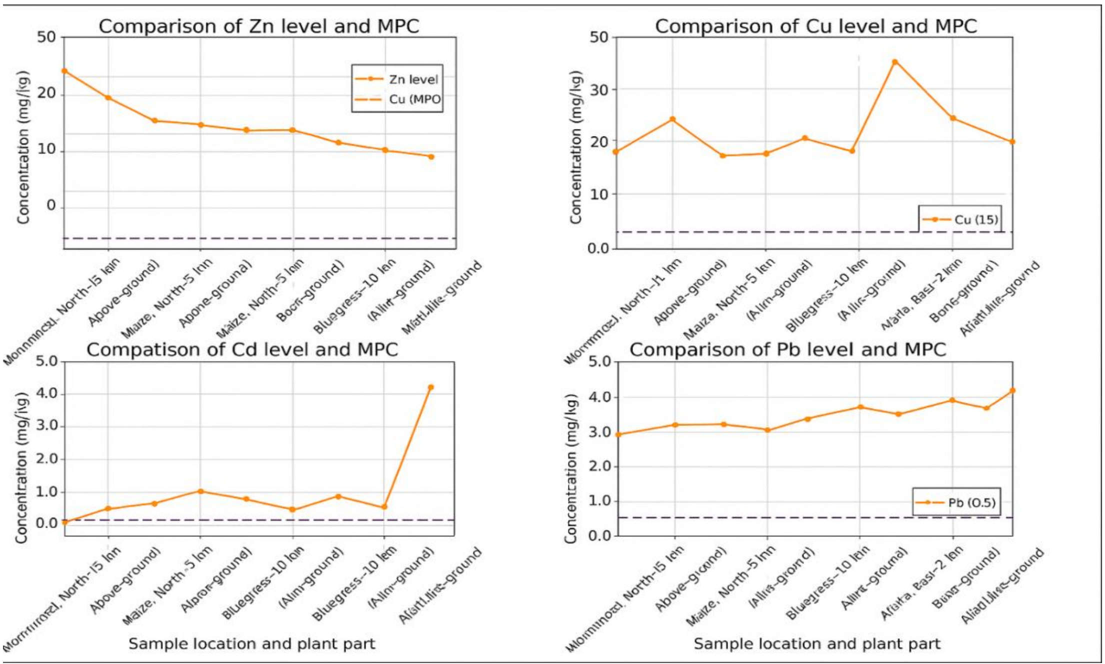

Fig. 7. Heavy metal concentrations (mg kg^{-1}).

CONCLUSION

Heavy metals are highly toxic substances that accumulate in soil as a result of anthropogenic impact. In the field of environmental protection, considerable attention is given to analyzing the presence of heavy metals in soil, since their concentrations affect biological conditions—particularly the functioning of microbiota—and interactions within the “soil-plant” system. Consequently, this influences the condition of local vegetation and, more broadly, the ecological state of the region, including public health. Analytical data on the acceptable concentrations of total and mobile forms of heavy metals in the studied site's soil indicate that the upper layers of the first soil pit show a slight increase in the total form of zinc: the concentration exceeds the Maximum Permissible Concentration (MPC) of 100 mg kg^{-1} by 1.85 times (or 85.2%) in the 0–14 cm layer, and by 1.01 times (or 10.1%) in the 14–25 cm layer. Similarly, cadmium exceeds its MPC of 5 mg kg^{-1} by 1.12 times (or 12%) in the 0–14 cm layer and by 1.2 times (or 20%) in the 14–25 cm layer. A slight increase in total Zn was also observed in soil samples from various parts of the agro-landscape. In the profile of the undisturbed regional soil, total Cd levels exceeded the MPC by 1.2 to 1.68 times across all layers. According to analytical data, the soils of surveyed areas around the "Kazphosphate" plants are contaminated by both mobile and total forms of zinc, cadmium, and copper (Zn, Cd, and Cu) at varying distances from the plant's main emission sources. Soil contamination is observed in all wind directions at depths of up to 30 cm. These elements are the dominant soil pollutants. The soils are mostly light-textured—sandy and light loamy—based on granulometric characteristics, which suggests a higher probability of heavy metal leaching into groundwater. This poses environmental hazards to ecosystems, including humans. Wind direction plays a key role in the dispersion of emissions. Areas located along the plant's prevailing wind direction are the most affected. Although emission density decreases by distance, local accumulation of pollutants can occur in areas with frequent calm conditions or geographical barriers. The accumulation of heavy metals (Zn, Cu, Cd, and Pb) in both aboveground and underground parts of plants such as alfalfa, maize, winter wheat, thistle, wormwood, and cereal crops indicates significant environmental pollution. The Zn and Cu levels in plants remain below dangerous levels and are considered safe. In contrast, the Cd and Pb concentrations exceed the MPC by several times—especially Cd in the western direction and Pb in all directions, particularly in the eastern and southern areas. These regions require monitoring and bioremediation measures to manage heavy metal contamination in both soil and vegetation.

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Bibliographic information of this paper for citing:

Yerkinbek, UY, Bakesova, RM, Sharipov, GA, Mendigaliyeva, AS, Zhylkyshybaeva, MM, Shalabayev, KY, Zhamalova, DB, Botbayev, DM 2025, Biogeochemical migration of heavy metals in the soil-plant system of Taraz, Kazakhstan: Effects of phosphorus plant emissions. Caspian Journal of Environmental Sciences, 23: 871-883.