

Spatial assessment of agro-landscape soil pollution by phosphorite plant emissions in semi-arid conditions

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ABSTRACT

This study presents a spatial assessment of agro-landscape soil contamination by phosphorite plant emissions under semi-arid conditions in the vicinity of Taraz, Kazakhstan. A total of 120 topsoil samples (0–20 cm) were collected from eight wind-oriented directions (N, S, W, E, NW, NE, SE, SW) at distances of 1, 2, 5, 10, and 20 km from the emission source. The chemical analysis included total and available forms of Zn, Cu, Cd, and Pb, while soil texture was classified based on granularity. Concentrations of total Zn exceeded the maximum permissible concentration (MPC: 100 mg/kg) in 12.5% of the samples, with the highest values observed along the northern and north-eastern transects. Available Cu also surpassed its MPC (3 mg/kg) in several sites located to the north and northwest of the plant. Pearson correlation analysis revealed a strong negative relationship between metal concentrations and distance from the pollution source, particularly for Zn ($r = -0.82$), Cu ($r = -0.65$), and Pb ($r = -0.59$). Additionally, a significant correlation was observed between total Cd and soil texture ($r = 0.88$ with granularity), highlighting the role of fine particles in metal retention. Principal Component Analysis (PCA) indicated that the first two components (PC1 = 33.1%, PC2 = 18.7%) accounted for over 50% of the variance. PC1 was driven by total and available forms of Zn and Cu, while PC2 was associated with Pb and soil texture. PCA biplot results clearly separated the northern and north-eastern directions from other sectors, corroborating the dominant wind directions identified from meteorological data (southerly and south-easterly flows). This anisotropic pattern of metal deposition suggests a prevailing wind-driven dispersion of contaminants from the phosphorite plant. The findings underscore the necessity of integrating wind-directional considerations into regional soil monitoring frameworks and provide a scientific basis for future environmental risk assessment and remediation planning in industrialized semi-arid zones.

Keywords: Phosphorite plant, heavy metals, environment, spatial analysis, semi-arid.

INTRODUCTION

Industrial activities exert a significant influence on environmental components, particularly the soil cover, especially in the vicinity of mining–chemical industry facilities (Aloud et al., 2022). Phosphorite processing plants, as major sources of particulate and gaseous emissions, release fluoride and phosphorus compounds as well as heavy metals, which accumulate in soil and impart toxic effects on plants, soil microbiota, and agro-ecosystems (Tanouayi et al., 2016; Toktar et al., 2022). The Zhambyl region is a major industrial hub in southern Kazakhstan, hosting one

of the country's largest phosphorite processing plants (Toktar et al., 2016). Operations at this facility generate persistent atmospheric emissions that, driven by wind transport, disperse contaminants over considerable distances. The intensity of this technogenic impact varies with wind direction and speed, local topography, and production rates (Toktar et al., 2017). Similar dispersion and accumulation patterns have been observed in arid and semi-arid environments, where low humidity and sparse vegetation facilitate the further spread and retention of pollutants on the soil surface (Quispe et al., 2024). The issue of soil contamination in areas surrounding phosphorite production facilities

has become particularly relevant in the context of sustainable development, where ensuring environmental safety and maintaining the productivity of natural ecosystems are key priorities (Singh et al., 2011). The disruption of soil structure and the degradation of agro-landscapes near emission sources lead to a reduction in biodiversity, loss of soil fertility, and, in some cases, a complete inability of the land to self-purify and recover (Kulymbet et al., 2023). As Drobitko et al. (2023), regions exposed to intense industrial pressure exhibit persistent transformations of soil horizons, accumulation of toxicants, alteration of hydro-physical properties, and a decline in biotic activity.

One of the distinctive features of pollution in arid regions is the high mobility and dispersion of contaminants (Tchounwou et al., 2012). Dry climate, sparse vegetation, and frequent winds facilitate the aerosol transport of pollutants over considerable distances from emission sources. This underscores the importance of not only quantitative assessments of pollution but also its spatial characterization (Hendrayana et al., 2025). Such phenomena have been thoroughly documented in studies evaluating the geochemical background and anthropogenic impacts on soils in arid regions of India and Africa (Eshete et al., 2023; Kumar et al., 2022). Internationally, research aimed at determining the spatial structure of pollution based on wind directions and landscape characteristics has become widespread (Ahmad et al., 2023). Geoinformation technologies, integration of wind rose maps and pollution zones, and modeling of anthropogenic flows enable the establishment of connections between emission sources and areas of highest ecological risk (Zhyrgalova et al., 2024). Specifically, the application of spatial interpolation methods, such as inverse distance weighting (IDW) and triangulated irregular network (TIN), reliably reconstructs emission dispersion zones and identifies geographic pollution priorities (Kaur et al., 2025).

The situation around the city of Taraz exemplifies a technogenic landscape impacted by chemical industry activities (Aliaskarov et al., 2025). A significant portion of the territory within a radius of several kilometers from the plant is occupied by agricultural lands, emphasizing the importance of ecological assessment of soil conditions (Kozybayeva et al., 2025). The presence of pollutants such as fluoride, heavy metals, and excessive phosphorus can adversely affect agroecosystems by reducing crop yields, disrupting trophic chains,

and posing risks to human health. Recent scientific studies increasingly emphasize the need for localized soil monitoring at the boundaries of industrial sanitary protection zones, particularly considering prevailing meteorological conditions (Béjaoui et al., 2016). Analyzing such data not only enables assessment of the current environmental status but also facilitates the development of scientifically-based mitigation measures. In the context of the phosphorite plant in Taraz, zoning of the territory according to contamination levels, followed by adaptive land-use strategies, preventive reclamation measures, and compensatory actions regarding affected land plots, has become particularly relevant.

Thus, investigating the spatial impacts of emissions from the phosphorite plant on the agro-landscape soils of southern Kazakhstan is an important task from both scientific and practical perspectives. The results of this research can contribute to the refinement of sanitary protection zone boundaries, assist in environmental management planning, and serve as a basis for long-term environmental monitoring and sustainable land use in areas influenced by technogenic sources of pollution.

The aim of this study is a comprehensive assessment of the spatial distribution of pollutant emissions from the phosphorite plant in the Zhambyl region and their impact on agro-landscape soils, considering wind rose patterns and directional pollutant transport.

Research objectives:

- 1) To assess the level of soil contamination in eight directions relative to the emission source;
- 2) To analyze the relationship between wind direction and the degree of soil contamination;
- 3) To identify areas of highest risk for agro-landscapes;
- 4) To conduct correlation and PCA analysis of soil physico-chemical properties and distance from the emission source in order to reveal spatial contamination gradients and identify key anthropogenic factors associated with phosphorite plant operations.

MATERIALS AND METHODS

Study area

The study area encompasses a 20-km radius around a phosphorite-processing plant in the western part of Taraz (Zhambyl region,



Figure 1. Phosphate plant and phosphogypsum waste dumps in Taraz city, Zhambyl region

Kazakhstan; $42^{\circ}55'35.55''$ N, $71^{\circ}18'56.03''$ E), totaling 125664 ha, which served as the emission source in this study (Figure 1 and 2). The region has a semi-arid climate with pronounced continentality; mean annual air temperature is $+11^{\circ}\text{C}$ and mean annual precipitation is $\sim 300\text{ mm yr}^{-1}$, with most rainfall occurring from spring to early summer. The terrain is a steppe plain with locally undulating relief at elevations of $\sim 600\text{--}700\text{ m a.s.l.}$ (Tastanbekova et al., 2025). Dominant soils are grey-brown (sierozem).

Land use is primarily rain-fed and irrigated agriculture and pastoral livestock grazing (Kozybayeva et al., 2025). Within the 20-km buffer, agro-landscapes are dominated by arable land and extensive pastures; built-up and industrial areas

(Table 1) are concentrated within the industrial zone and along transport corridors, producing a fragmented land-use mosaic. The surrounding open landscapes and agricultural fields are potentially affected by aeolian transport of pollutants originating from the plant.

Soil sampling

Fieldwork was conducted in eight directions from the emission source: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW). In each direction, sampling sites were established at distances of 1 km, 2 km, 5 km, 10 km, and 20 km from the phosphorite plant. The prevailing

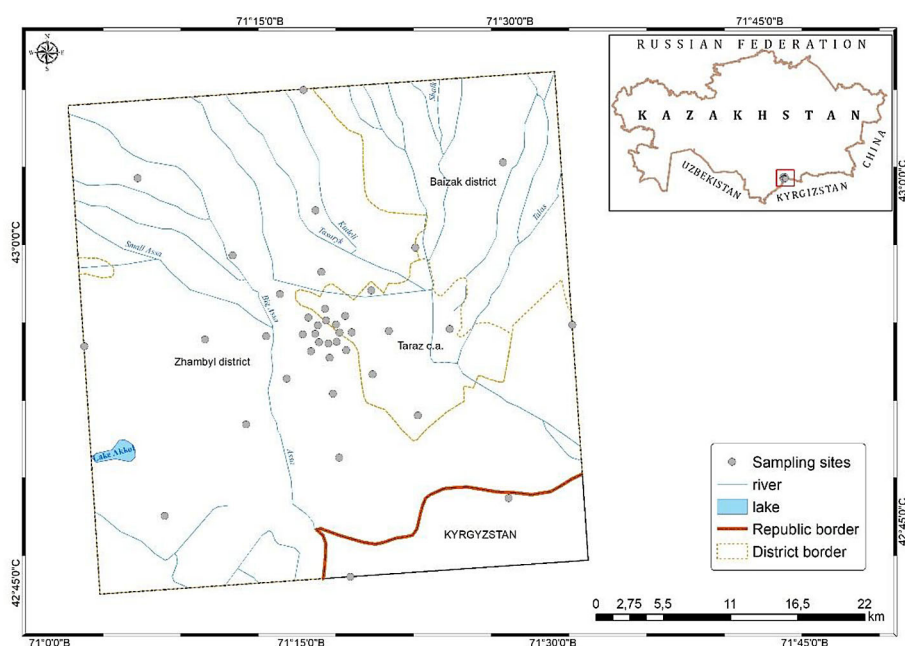


Figure 2. Distribution of the study area and sampling sites

winds originate from the south and southeast, a factor taken into account when planning the directions of soil sampling transects. A total of 120 soil samples were collected. Samples were taken from the topsoil layer (0–20 cm) following standard procedures for agrochemical and environmental monitoring.

Laboratory analysis

All soil samples were carefully air-dried at a temperature not exceeding 40 °C in the shade, and then sieved through a 1 mm mesh to remove coarse particles. A representative subsample was prepared from each composite sample for chemical and physico-chemical analysis. Soil pH was determined in a water extract (soil-to-water ratio of 1:2.5) using a laboratory-grade pH meter. Electrical conductivity (EC) was also measured in the water extract and served as an indicator of soil salinity and the overall content of soluble salts.

The contents of heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) were determined using atomic absorption spectrophotometry (AAS) after acid digestion of the soil samples in accordance with ISO 11466 standard (FAO Standard, 2025). This method provides high analytical accuracy in determining metal concentrations across various soil types. Soil pH was measured in a soil-to-water ratio of 1:2.5 using an I-160MI pH meter (Russia, 2007). The granulometric composition of soils was determined by the sedimentation method of A.A. Kachinsky, based on the settling velocity of particles in an aqueous suspension (Vanchikova et al., 2024).

Statistical processing and spatial analysis

To identify the relationship between the level of contamination and the distance from the emission source, Pearson's correlation coefficient was used. Statistical data processing was performed using the R-Studio environment (2020). This method allows for the assessment

of the linear degree of association between two quantitative variables (Benesty et al. 2009). The correlation coefficient was calculated using the following formula:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2}} \quad (1)$$

where: x_i and y_i – values of the variables, $\bar{x}$ and $\bar{y}$ – mean values.

Correlation analysis was used to assess the relationship between soil physico-chemical properties (EC, pH, fluorine, P₂O₅, etc.) and the distance from the emission source. Prior to analysis, the data were tested for normality using the Shapiro–Wilk test. Only parameters with normally distributed values were included in the correlation calculations. Correlations were considered statistically significant at a threshold of $p < 0.05$. The strength of the correlation was interpreted according to the standard scale: weak ($r < 0.3$), moderate ($0.3 \leq r < 0.7$), and strong ($r \geq 0.7$).

To identify the key factors influencing the spatial variability of heavy metal concentrations and soil properties in different directions from the emission source, PCA was applied (Liu et al., 2023). The analysis was conducted using standardized data for eight heavy metal indicators (Zn, Cu, Cd, Pb in both total and available forms), as well as granulometric composition. The suitability of the dataset for PCA was evaluated using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. All variables were auto-scaled (i.e., standardized to zero mean and unit variance) to eliminate the influence of differing measurement units. To determine the number of principal components, the eigenvalue criterion (eigenvalue > 1) was applied, and Varimax rotation was used to improve interpretability. The analysis of loading plots and biplots enabled the identification of variables with the highest contribution to component formation and visualized the differentiation between sampling points based on their

Table 1. Land-use within the 20-km buffer around the phosphorite-processing plant in western Taraz

Land-use class	Share, %	Area, ha	Area, km ²
Cropland (rain-fed and irrigated)	57	71628.48	716.28
Pastures	14	17593.0	175.93
Built-up/industrial + urban	19	23876.12	238.76
Other surfaces (shrub-grassland, bare, water)	10	12566.40	125.66
Total	100	125664.0	1256.63

distance and direction relative to the emission source. This approach allowed for a more accurate interpretation of pollution dispersion trends and soil resilience under semi-arid climate conditions. All statistical analyses were performed in the R-Studio environment.

The spatial visualization of physico-chemical properties and soil contamination was carried out in ArcGIS using the IDW interpolation method to construct distribution maps for the studied pollutants. The main steps included georeferencing the sampling points, creating thematic layers for each chemical parameter, and comparing them with prevailing wind directions.

The applied methodological framework provides an objective assessment of technogenic pressure on agro-landscape soils and identifies spatial patterns in the dispersion of emissions from the phosphorite plant.

RESULTS

Spatial analysis of physico-chemical variables

Granulometric analysis of 120 topsoil samples revealed the predominance of sandy loam soils (with clay particle content ranging from 10 to 20%), which accounted for 62.5% of the total sampling points. Light loams (20–30%) were found in 22.5% of cases, while sandy soils (<10%) and medium loams (30–45%) were each identified at only 7.5% of the sites. No heavy loam soils (>45%) were recorded in the study area (Figure 3).

This distribution indicates that the agro-landscape soils surrounding the phosphorite plant are

mainly characterized by low to moderate clay content, which significantly influences their sorption capacity and the mobility of heavy metals. Sandy and sandy loam soils have low cation exchange capacity and limited water-holding capacity, which enhances infiltration and horizontal migration of pollutants such as Zn, Cu, Cd, and Pb. In contrast, heavier textured soils-especially those found in the northern and southeastern directions-may act as accumulators due to their higher adsorption potential and tendency to form aggregates capable of binding metals.

Particular attention should be given to the northwestern and southeastern sectors, where a greater number of light and medium loam soils were identified, along with elevated concentrations of heavy metals (Figure 4). This spatial overlap suggests that granulometric composition plays a secondary but reinforcing role in pollutant accumulation-especially when combined with prevailing wind directions and proximity to the emission source. From an environmental monitoring perspective, the observed soil texture distribution is of significant importance for modeling ecological risks, as it enables the identification of zones with a high potential for contaminant leaching versus areas of accumulation.

Soil pH values in the studied samples ranged from 7.96 to 8.96, with an average of 8.60. All soils were classified within the alkaline range. Alkaline soil reaction plays a critical role in determining the behavior of heavy metals, including their solubility and mobility (Xu et al., 2024). Specifically, at pH levels above 8.0, the solubility of cadmium and lead decreases, while their adsorption onto clay particles and carbonate compounds increases.

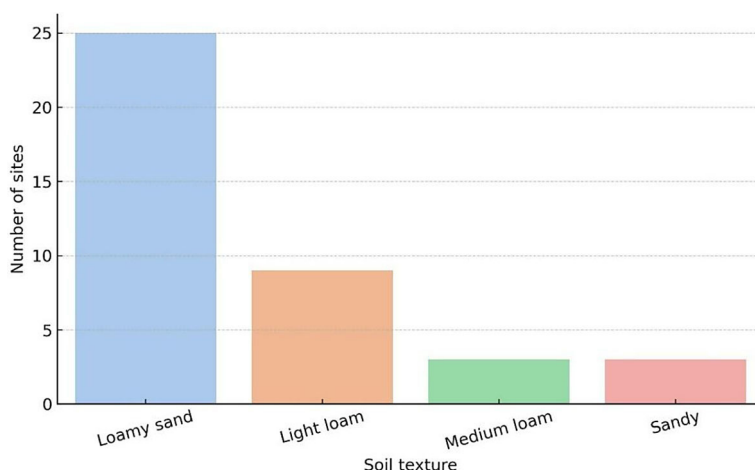


Figure 3. Soil texture classification by granulometric composition

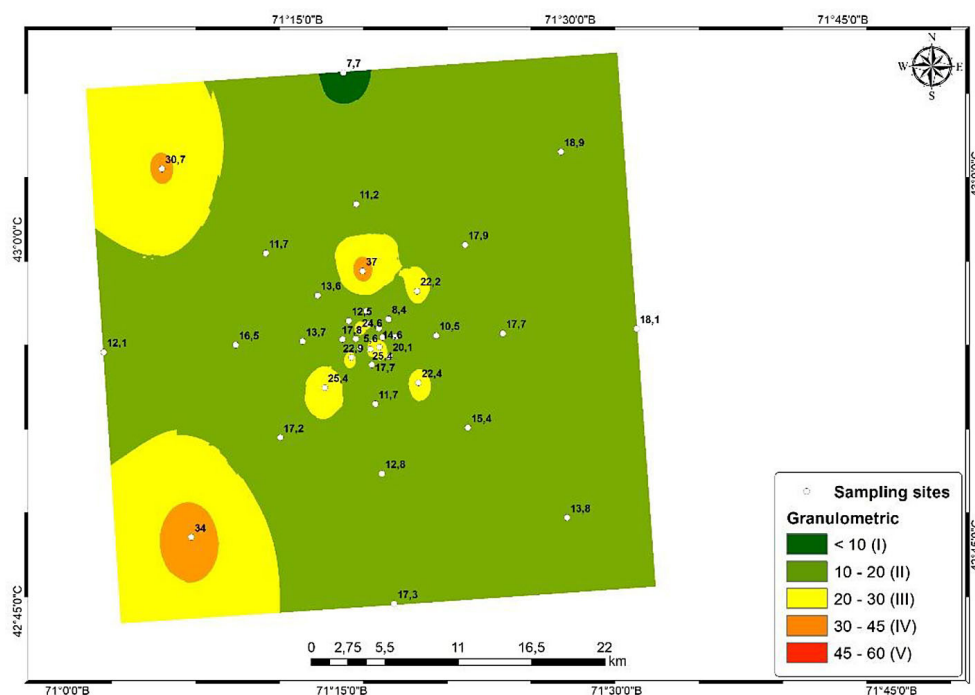


Figure 4. Spatial distribution of the granulometric composition of soils

Spatial analysis of heavy metals

The conducted analysis of heavy metal content (zinc, copper, cadmium, lead) in agro-landscape soils adjacent to the phosphorite plant in the city of Taraz revealed distinct spatial patterns that reflect the degree of anthropogenic pressure. The study covered eight principal directions (north, northeast, east, southeast, south, southwest, west, northwest), with soil sampling carried out at distances of 1, 2, 5, 10, and 20 km from the emission source. This approach enabled not only an assessment of overall contamination but also an evaluation of the influence of atmospheric factors on the dispersion of pollutants.

Zinc (Zn)

The total zinc concentration reached 444 mg/kg at a distance of 1 km north of the plant, exceeding the maximum permissible concentration (MPC) for total Zn (100 mg/kg) by a factor of 4.4. A similar pattern was observed for the available form of Zn, with maximum values (79 mg/kg) recorded within 2 km of the source. Beyond 10 km, concentrations decreased to background levels (Figure 5). Correlation analysis revealed a strong negative relationship between zinc concentration and distance from the emission source ($r = -0.72$), confirming the anthropogenic origin of the contamination. The highest exceedances were found

in the southern and southeastern directions, indicating the influence of windborne transport.

Copper (Cu)

Total copper concentrations also exceeded the MPC (55 mg/kg) near the plant. The highest value was recorded at SE-2 km (135.6 mg/kg), which is 2.5 times the permissible level. The available form of copper exceeded the MPC (3 mg/kg) up to 2 km in almost all directions (Figure 6). The Pearson correlation coefficient between copper concentration and distance was -0.61 , indicating a consistent decrease in contamination with increasing distance from the source.

Cadmium (Cd)

The behavior of cadmium was less predictable. Although elevated total Cd concentrations were observed at specific locations (e.g., NE-5 km and NW-10 km), reaching up to 12 mg/kg-exceeding the maximum permissible concentration (MPC) of 5 mg/kg-no clear spatial trend was detected (Figure 7). The Pearson correlation coefficient between cadmium content and distance was $+0.18$, possibly indicating secondary migration processes, microrelief influences, or seasonal variability. Nevertheless, even in the absence of a strong spatial pattern, more than half of the sampling points within 5 km

exhibited elevated levels of available Cd above the MPC of 2 mg/kg.

Lead (Pb)

Total lead concentrations exceeded 22 mg/kg at sampling points located 1–2 km from the plant, particularly in the northern and southern directions. While most values remained below the total Pb MPC (30 mg/kg), the concentration of available lead frequently exceeded the hygienic threshold (6 mg/kg), indicating potential bioavailability and risk of entry into trophic

chains (Figure 8). Correlation analysis revealed a moderately negative relationship with distance ($r = -0.42$).

Features of the southern and southeastern directions (wind rose analysis)

The analysis of the southern (S) and south-eastern (SE) sectors-corresponding to the prevailing wind directions in the study region-revealed the highest levels of soil contamination by heavy metals. This finding confirms the dominant role of atmospheric transport as a key mechanism for

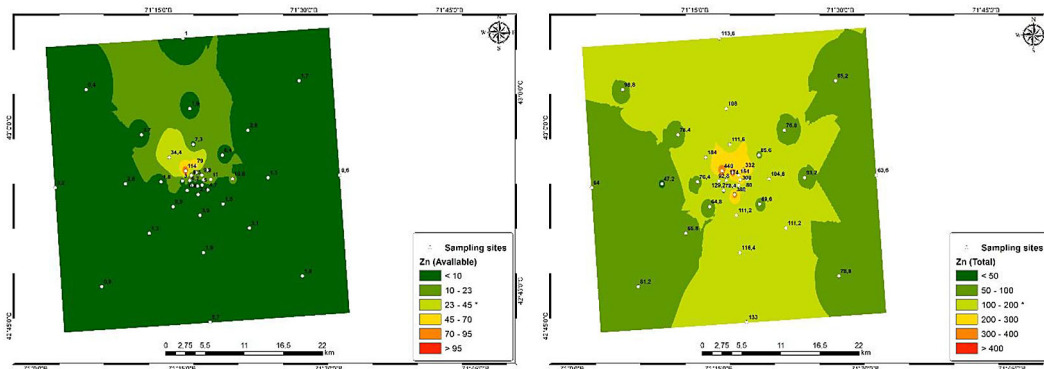


Figure 5. Spatial distribution of available and total zinc (Zn) in soils of the Zhambyl region

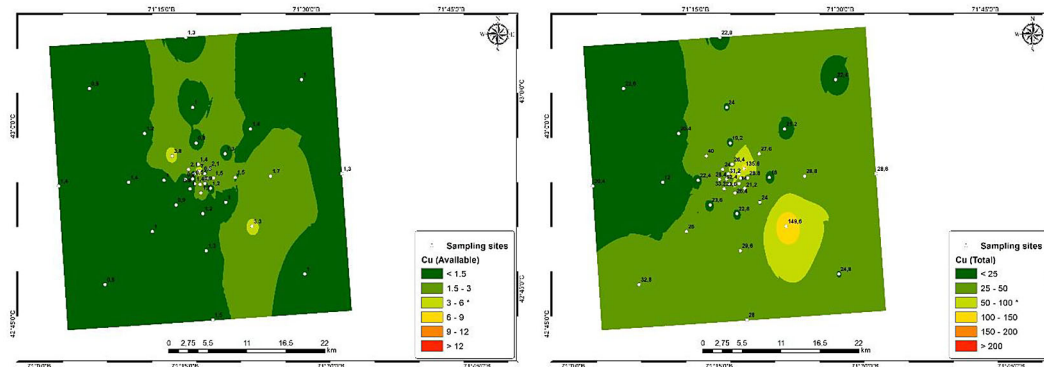


Figure 6. Spatial distribution of available and total copper (Cu) in soils of the Zhambyl region

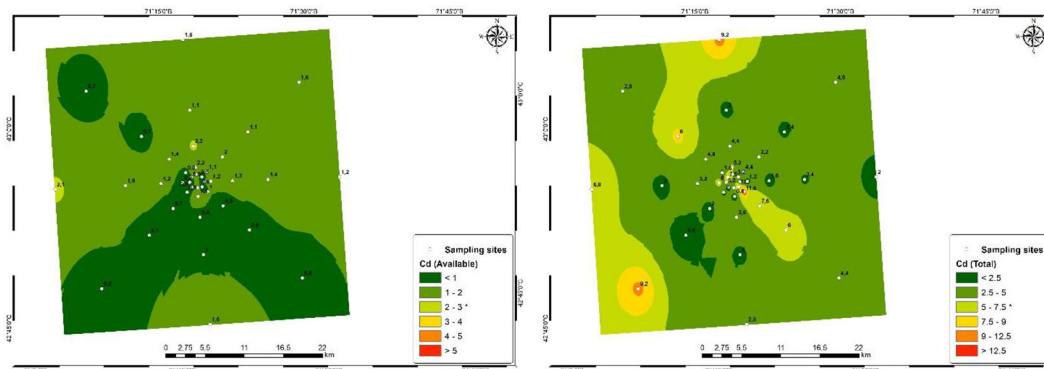


Figure 7. Spatial distribution of available and total cadmium (Cd) in soils of the Zhambyl region

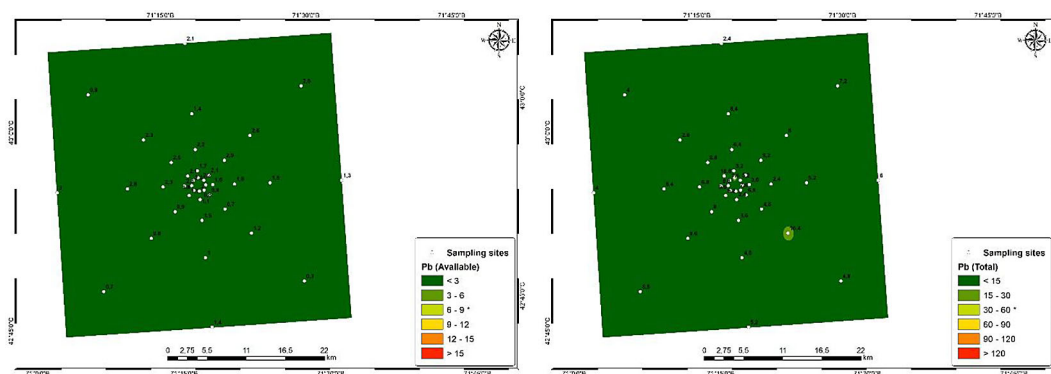


Figure 8. Spatial distribution of available and total lead (Pb) in soils of the Zhambyl region

pollutant migration from the emission source. The highest exceedances of Zn, Cu, and Pb concentrations were recorded in these directions. Regression analysis demonstrated clear decreasing trends for these metals with increasing distance from the source, with the steepest regression slopes observed in the S and SE sectors. This was particularly evident in the SE direction, where the difference in total Zn concentration between 1 km and 5 km exceeded 300 mg/kg, and for total Cu surpassed 100 mg/kg. These results highlight the high intensity of pollution within the emission impact zone.

In contrast, Cd concentrations in these directions were more variable and did not exhibit a consistent trend, suggesting the need for further investigation into its speciation, mobility, and potential sources (Figure 9).

Exceedance of MAC and ecological risks

Comparison of the obtained data with the maximum allowable concentrations (MAC) revealed that at distances up to 2 km from the emission source, nearly all directions demonstrated exceedances for zinc (both total and available forms), copper, and cadmium. In the southeastern direction, total Zn levels exceeded the MAC by more than four-fold, while total Cu levels surpassed the standard by more than twofold. The concentration of available Pb in certain sampling points reached up to 16.4 mg/kg, exceeding the sanitary threshold by 2.7 times. These findings emphasize the necessity of establishing continuous soil monitoring programs and conducting agroecosystem risk assessments.

Ecological consequences

The results indicate significant local contamination of agro-landscape soils within a 5 km radius of the phosphorite plant, particularly in the southern and southeastern sectors. The

exceedance of MAC by mobile forms of heavy metals poses the greatest threat to plants, soil microbiota, and potentially to food chains. Given the region's semi-arid climate, where natural leaching and soil self-purification processes are considerably limited, there is a high risk of long-term retention and persistence of contaminants in the environment.

Correlation and PCA analysis

To assess the relationships between the content of heavy metals (both total and available forms) and the granulometric composition of agro-landscape soils surrounding the phosphorite plant, a Pearson correlation matrix was constructed (Figure 10). This analysis revealed several statistically significant dependencies that shed light on the spatial distribution and potential bioavailability of elements under semi-arid climatic conditions.

A strong positive correlation was found between the total and available forms of zinc ($r = 0.57$), copper ($r = 0.64$), and lead ($r = 0.55$), indicating a stable geochemical link between the total metal content and its mobile fraction in soils. This suggests that anthropogenic inputs—likely associated with emissions from the phosphorite plant—contribute both to the accumulation of heavy metals and to the formation of potentially hazardous mobile forms, increasing the ecological risk.

Total forms of lead and copper also exhibited strong mutual correlations ($r = 0.66$ and $r = 0.65$, respectively), which may indicate their co-deposition or similar migration behavior under local soil and climatic conditions. These findings are consistent with other studies conducted in industrial areas, where Zn, Pb, and Cu commonly show similar accumulation patterns in topsoil due to atmospheric deposition and particulate emissions

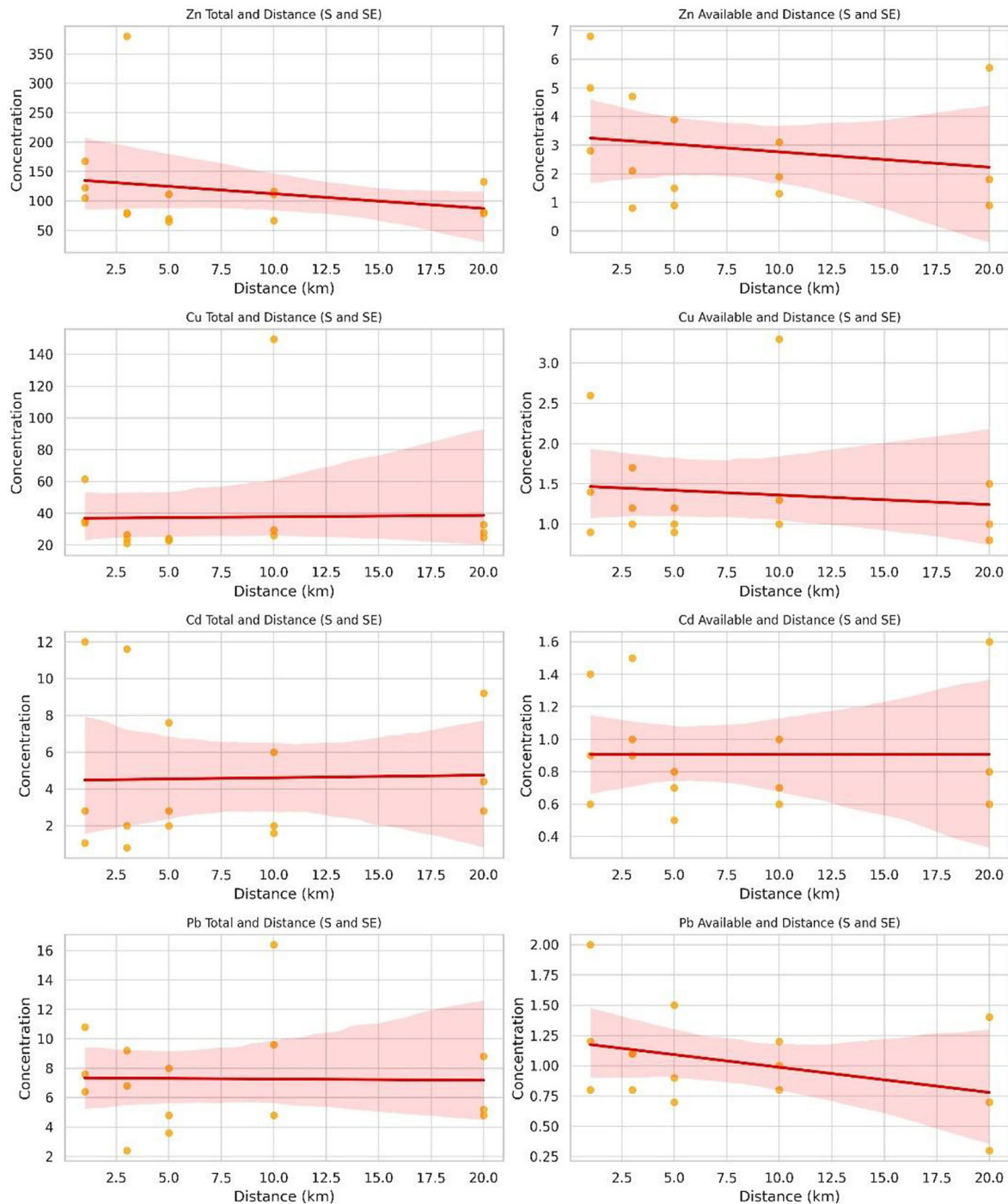


Figure 9. Dependence of heavy metal concentrations in soil on the distance from the emission source in the southern and southeastern directions (wind rose analysis)

(Tóth et al., 2016). Notably, cadmium showed a weak or nearly absent correlation between its total and available forms ($r = 0.07$), suggesting high mobility and weak association with background concentrations. This may be attributed to its greater solubility and leaching potential, or uptake by plants—especially under the slightly alkaline soil conditions typical of the study area (Alloway, 2013).

Regarding granulometric composition, correlations with metal contents were predominantly weak or negative. The most pronounced absolute value was observed between *Gran_soil* and total lead ($r = -0.17$), indicating that heavier-textured soils in this case do not necessarily accumulate more lead. These findings differ from observations in more humid regions with high clay content, where significant sorption of metals onto

fine particles is typically reported (Kabata-Pendias and Mukherjee, 2007).

The lack of a clear relationship between soil texture and metal concentrations suggests that the spatial variability of contamination is largely driven by proximity to the emission source and prevailing wind patterns, rather than by the physicochemical properties of the soil itself. This interpretation is further supported by the regional wind rose, which indicates dominant air mass movement in southern and southeastern directions—precisely the sectors where elevated concentrations of zinc and lead were recorded.

To assess the spatial distribution of heavy metals and soil textural characteristics in agro-landscapes affected by emissions from the phosphorite plant, a Principal Component Analysis (PCA) was conducted, covering eight sampling directions (N, S, W, E, NW, NE, SE, SW) (Figure 11). Figure 10 presents the samples labeled by direction, accompanied by 95% confidence ellipses, along with variable vectors (metal concentrations and granulometric composition) indicating their contributions to PC1 and PC2 axes.

The first principal component (PC1), explaining 33.1% of the total variance, is primarily correlated with the total and available concentrations of Zn and Cu. The orientation of the vectors

for Zn (total), Zn (available), Cu (total), and Cu (available) suggests their strong positive influence on the formation of this component. The second principal component (PC2), accounting for 18.7% of the total variance, is more strongly associated with the granulometric indicator reflecting the proportion of heavier soil fractions. The samples collected from the northern direction (N) are clustered in the upper right quadrant, reflecting high values of both PC1 and PC2. This indicates substantial accumulation of heavy metals and a clay-rich soil texture, which is consistent with the prevailing wind directions (south and southeast), and therefore, a higher likelihood of pollutant deposition from the plant's emissions.

In contrast, sample groups from the southwest (SW), south (S), and east (E) directions are primarily located in the lower and left quadrants of the PCA biplot, indicating relatively low metal concentrations and lighter soil textures (sandy loam and light loam). The NW and NE directions exhibit considerable variability within their confidence ellipses, suggesting heterogeneous levels of contamination.

The PCA analysis clearly reveals spatial differences in soil contamination and texture depending on direction relative to the plant, confirming the significant influence of emissions, particularly in wind-exposed zones (notably the N and NE sectors).

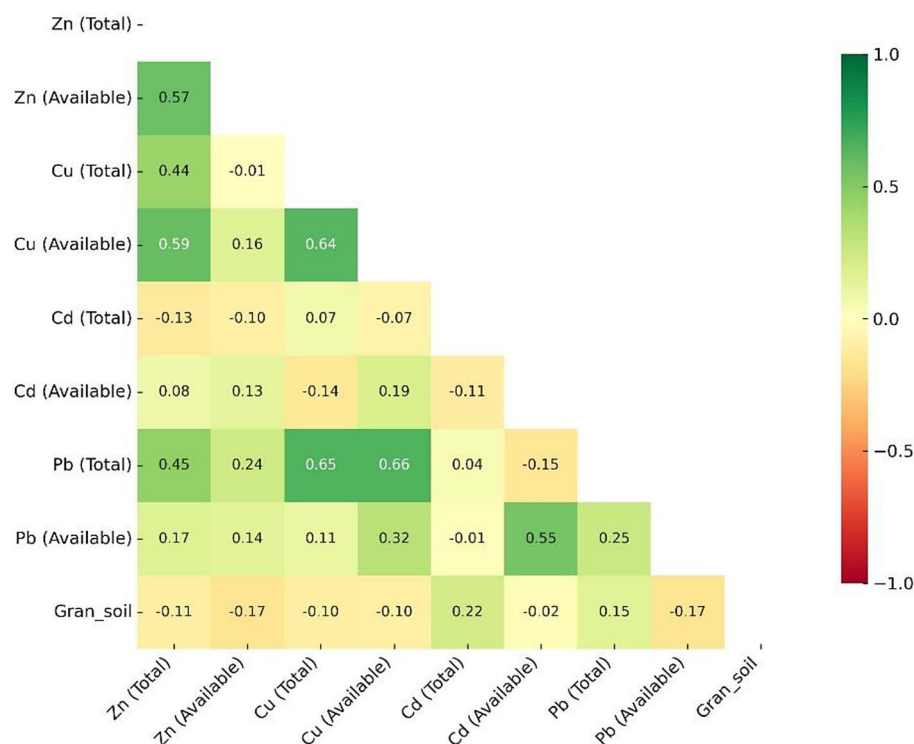


Figure 10. Pearson correlation matrix between total and available forms of heavy metals and soil granulometric composition in the vicinity of the phosphorite plant

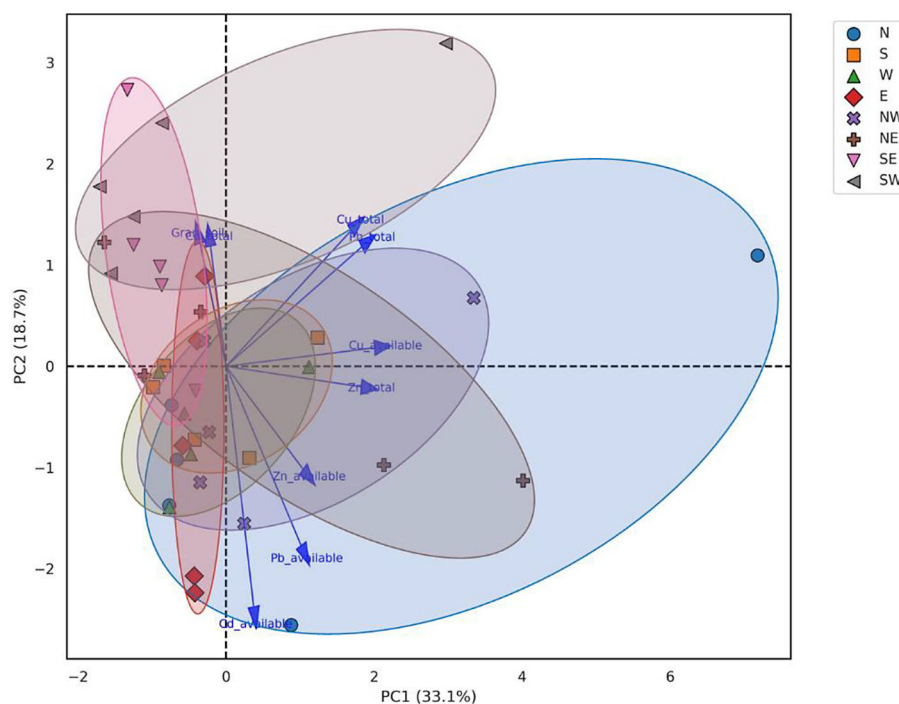


Figure 11. Principal component analysis (PCA) of soil heavy metals and texture by wind directions

DISCUSSION

The results obtained are consistent with trends identified in several other studies focused on soil contamination from industrial emissions. According to Bayazitova et al. (2023), the concentrations of heavy metals in soils adjacent to chemical and metallurgical facilities sharply decrease with increasing distance from the emission source, particularly when wind direction is taken into account. A similar effect was observed in the present study, especially for Zn and Cu, whose levels exhibited the strongest distance-dependent gradients ($r = -0.72$ and $r = -0.61$, respectively).

The work of Hadzi et al. (2024) demonstrated that mobile (available) forms of metals are more informative for assessing potential risks to agroecosystems, as they are directly bioavailable to plants and soil microbiota. Our findings corroborate this conclusion: the concentrations of available Zn, Cu, and Pb frequently exceeded hygienic thresholds at distances up to 2–5 km from the emission source.

Moreover, studies conducted in the Turkestan region by Zhanibekov et al. (2021) emphasize the importance of assessing the spatial differentiation of contamination depending on wind direction and intensity. In our study, the highest concentrations of heavy metals were observed precisely along the prevailing wind directions—south

and southeast. This finding fully aligns with the pollutant aerodispersion model described by Omo-Okoro et al. (2025), which suggests that heavy metals tend to accumulate in the windward sectors within a radius of up to 5 km from the emission source. The specific spatial pattern of cadmium (weak correlation and relatively uniform presence) also supports the findings of Luo et al. (2019), who reported that cadmium exhibits high mobility, particularly in dry and neutral soils, and may migrate independently of the main pollutant plume.

The results of this study are consistent with existing data on the aeolian migration of pollutants, as reported by Al-Khashman and Shawabkeh (2006) and Kubier et al. (2019), which emphasize the critical role of wind direction, landscape structure, and microrelief features. Sikdar et al. (2022) also highlight the presence of spatial contamination mosaics within a single landscape unit, attributed to microtopography and variability in vegetation cover.

Comparative findings are presented in studies of phosphate-processing facilities in Central Asia, where anthropogenic pressure has persisted for decades (Suska-Malawska et al., 2022; Baubekova et al., 2021). Under arid conditions, reduced leaching and biodegradation processes contribute to the prolonged retention of heavy metals in the upper soil horizons (Muratbayeva et al., 2025).

The presence of elevated concentrations of mobile forms of Cu, Zn, and Pb within a 2 km radius is of particular concern, as these species are readily incorporated into food chains. They pose a threat not only to agricultural crops but also to soil microflora, potentially disrupting biogeochemical cycles (Angon et al., 2024).

It is also important to note the findings of Mueller et al. (2014), which demonstrated that heavy metals tend to persist longer in agricultural soils (agrolandscapes) due to intensive mechanical disturbance, limited bioturbation, and homogeneous texture. This is especially relevant for soils with predominant sandy loam and loam horizons-features characteristic of the study area.

A similarly unstable spatial pattern of Cd was reported in studies of agricultural regions in India (Verma, 2022), where its distribution was found to depend on soil pH, texture, and organic matter content. In the semi-arid climate of southern Kazakhstan, where humus accumulation processes are limited, cadmium migration may be governed by abiotic factors such as evaporation and wind erosion.

According to Cao et al. (2022), exceeding permissible levels of mobile metal forms in agrolandscapes highlights the urgent need for environmental protection measures. In our study, exceedances of the maximum allowable concentrations for Zn, Cu, Cd, and Pb were recorded in most directions within 5 km of the pollution source, emphasizing the necessity of establishing sanitary protection zones and reconsidering agricultural practices on adjacent farmlands.

Thus, comparison with the findings of other studies demonstrates that the phosphorite plant in Taraz exerts a pronounced anthropogenic impact on agro-landscape soils. The spatial structure of pollution, its dependence on wind direction and distance from the emission source, as well as exceedances of maximum permissible concentrations for bioavailable metal forms, confirm the relevance and reliability of the obtained data. Future research should focus on the seasonal dynamics of pollution, its biological consequences, and the effectiveness of potential remediation measures.

CONCLUSIONS

The study revealed that emissions from the phosphorite plant in Taraz cause significant contamination of agro-landscape soils with heavy

metals, particularly in the southern, southeastern, and northern directions, which correspond to the prevailing wind rose. Concentrations of Zn, Cu, and Pb decrease with distance from the emission source, confirming the airborne nature of pollutant dispersion. The observed exceedances of maximum permissible concentrations (MPCs) pose an environmental threat and highlight the need for the establishment of sanitary protection zones and continuous monitoring. The obtained data can serve as a basis for environmental planning and reducing anthropogenic pressure on soil resources.

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