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# Investigation of Possible Negative Consequences of Environmental Pollution by Phosphorite Production Wastes

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## Abstract

The rapid expansion of phosphorus production has emerged as a critical environmental issue, disrupting the balance between industrial growth and ecological stability. Kazakhstan, as a leading phosphorus producer, faces significant challenges due to the environmental impact of activities in the Karatau phosphate basin. This study evaluates the environmental consequences of Kazphosphate LLP's operations in Karatau, focusing on air quality, surface water pollution, heavy metal contamination in soil, and the formation of young soils at industrial waste sites. Key findings include elevated zinc levels in soil samples, exceeding the maximum permissible concentration by up to 12 times, and low concentrations of copper. The air quality in Karatau showed low pollution levels, with hydrogen sulfide ($H_2S$) at acceptable limits with a standard index (SI) of 0.9. The water bodies, particularly the Talas and Assy rivers, exhibited moderate pollution, with magnesium and sulfates as primary contaminants. Soil analysis highlighted the slow progression of natural recovery, with higher humus and mobile phosphorus content in the upper layers, but deficiencies in nitrogen and exchangeable potassium. This research underscores the urgent need for sustainable waste management practices, reclamation strategies, and advanced technologies to mitigate the environmental impact of phosphorus production. The findings aim to inform measures to reduce pollution, enhance ecosystem restoration, and promote the long-term sustainability of the Karatau phosphate basin.

*Keywords:* Phosphorite production; Environmental pollution; Heavy metals; Soil contamination; Public health impact; Waste management.

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## 1. Introduction

The rapid intensification of anthropogenic impact on the environment has become a significant factor influencing planetary processes. This is further exacerbated by the growing global population and the continued advancement of the scientific and technological revolution, which have amplified the scale of human influence on natural systems.[1,2] In this context, several global environmental challenges have emerged, including environmental pollution, food security, access to industrial minerals, and energy supply.[3,4] Among these, environmental protection from pollution is the most pressing issue for the Republic of Kazakhstan. Pollution of the atmosphere, along with domestic and industrial waste, has become a critical problem in Kazakhstan's single-industry towns. Although the specifics of these challenges vary across different towns, the overarching issue is the serious threat that they pose to human life and health. This is evident in the rising rates of respiratory cancers, maternal and child mortality, and the increasing number of births involving congenital disabilities in populations residing in single-industry towns and industrial cities.[5-7] These problems are compounded by inadequate environmental protection measures, which hinder efforts to mitigate pollution and its harmful effects. Addressing these challenges requires a commitment to

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achieving harmony with nature, as sustainable solutions are unattainable without prioritizing environmental stewardship.

Currently, single-industry towns account for 32% of urban settlements in Kazakhstan, comprising 27 towns. The majority (59%) are located in the industrially developed regions of Karaganda, Kostanay, and East Kazakhstan.[8] According to local executive bodies, only 22.2% of these towns, including Aksu, Ekibastuz, Ridder, Rudnyi, Temirtau, and Khromtau, are classified as cities with high economic potential. In contrast, 70.3% have medium economic potential, while Arkalyk, Zhanatas, and Karatau (7.5%) are categorized as cities with low economic potential.[9,10] Since 1999, the population of single-industry towns has declined significantly, decreasing from 3 million to 1.5 million. This reduction is largely due to the migration of the economically active population to other regions and cities. While socio-economic factors are the primary drivers of resettlement, environmental issues have also played a significant role in this decline. Addressing these environmental challenges is therefore critical for ensuring the sustainable development of single-industry towns.[11,12] The failure of earlier programs, such as the 2004–2006 Program for the Development of Small Towns and the 2012–2020 Program for the Development of Single-Industry Towns, underscores the importance of integrating environmental considerations into development strategies. Without adequately addressing these issues, the long-term growth and viability of single-industry towns remain at risk.[13]

A major concern today is the environmental condition of the single-industry town of Karatau, located northwest of the city of Taraz. Once one of the largest single-industry towns in Kazakhstan, Karatau faces significant environmental challenges, primarily due to the phosphorus production. The extraction and processing of phosphorite can disrupt the balance between society and nature, leading to severe environmental problems, including water and soil pollution. Existing studies have provided some insights into the issue. For instance, Abildayeva *et al*.[14] explored the potential use of mine phosphate rock and waste from the Karatau-Zhambyl territorial-industrial complex (TIC) and phosphate plants. Shanbayev *et al*.[15] conducted pilot tests and feasibility studies on phosphate industry waste from the Zhambyl region, demonstrating the cost-effectiveness of producing a non-flammable binder for the construction industry from this waste. Similarly, Seraya *et al*.[16] investigated the chemical and mineralogical composition of by-products obtained from processing phosphate rock at the Projected Chemical Complex of EuroChem-Karatau Company. Despite its importance, the pollution of soil, water, and plants by heavy metals such as lead (Pb), copper (Cu), cadmium (Cd), and zinc (Zn) in the phosphate basin of Karatau has not been fully investigated. This is a critical issue, as heavy metal contamination of soil and water can transfer to plants, crops, and animals, ultimately posing serious health risks to humans who consume them. For instance, Cd and Zn contamination can lead to the kidney damage, gastrointestinal disorders, and respiratory tract cancer. In terms of soil quality, elevated Zn concentrations disrupt the balance of essential nutrients, adversely affecting the overall health and productivity of ecosystems. Zinc toxicity also inhibits the growth of beneficial soil microorganisms and interferes with nutrient cycling, which reduces soil fertility and negatively impacts the agricultural productivity and food security.

This study is highly relevant as it seeks to evaluate the environmental impact of Kazphosphate LLP, a major industrial enterprise in Karatau, on the surrounding ecosystem. Although phosphate rock mining activities in Karatau (notably in Sholaktau, Aksai, and Shylybulak) have been ongoing, their environmental effects remain poorly understood. Limited research has systematically assessed the pollution of water bodies by phosphorite production waste, the extent of atmospheric pollution, adverse effects on local flora and fauna, and potential methods for mitigating these pollutants. The methodological framework of this study was built upon a comprehensive review of global literature,[17-31] providing a foundation for analyzing key environmental issues. These include atmospheric emissions, eutrophication of water bodies, land degradation caused by phosphogypsum near the deposit, and soil and environmental pollution in the single-industry town of Karatau. The findings aim to contribute to the development of effective measures and programs to mitigate air pollution from industrial activities and transportation, water pollution from mining and industrial waste, illegal dumping, and soil contamination. Moreover, this study serves as a valuable resource for research focused on preserving ecosystems and wildlife. Addressing the prevention of harmful chemicals and waste from entering the air and water provides practical insights into safeguarding the environment and promoting sustainable development in Karatau.

## 2. Materials and methods

### 2.1 Study area

Kazphosphate LLP is the leading producer of phosphate-containing products in the Republic of Kazakhstan.[32] It is located in the Karatau phosphate basin near the single-industry town of Karatau, the administrative center of the Talas district in the Zhambyl region. The Karatau phosphate basin spans 100–120 km in length and 25–30 km in width.[33] Within the exposed phosphorite horizon, 49 deposits have been identified, most of which are directly managed by Kazphosphate LLP (Fig. 1).

These deposits are classified into five regional groups based on their location and significance:

- The First Group: It includes the large Sholaktau phosphate rock deposit and smaller deposits such as Tamdy, Arbatas, Suleymensai, Nasynkul, Kotyrbulak, and Zhetymchoki, which have very low production value.
- The Second Group: It encompasses the large Aksai and Tuesai phosphorite deposits, along with smaller reserves in Koktal, Tesiktas, and Kyrshabakty.
- The Third Group: It comprises smaller fields, including

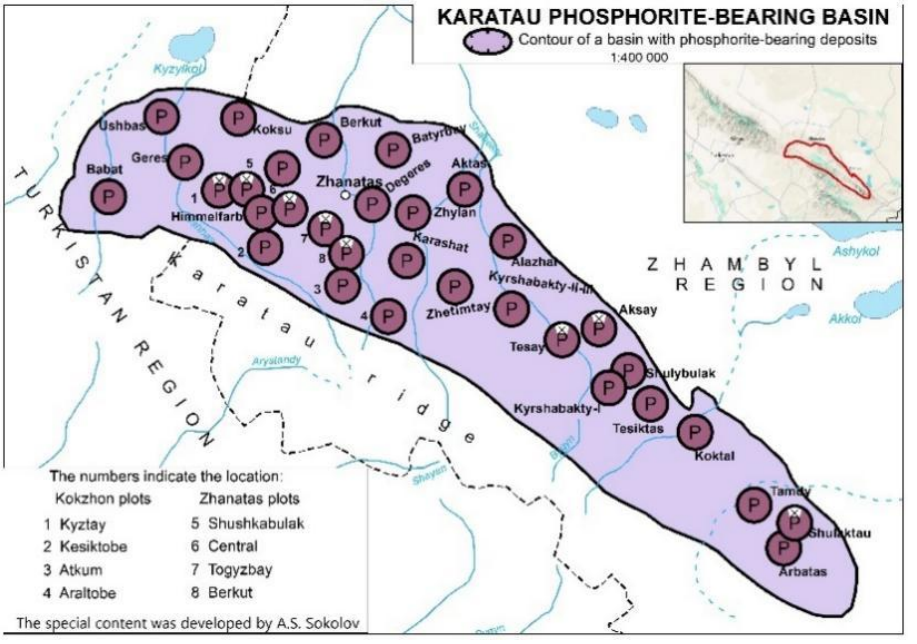



**Fig. 1:** Map of the Karatau phosphorite basin according to A. S. Sokolov.[34]

Zhetimtal, Burkitti, Aktas, and Karashat, which have limited industrial significance and are located between the Aksai and Koksu fields.

- The Fourth Group: It includes a mix of industrial and smaller deposits such as Akzhar, Ushbas, Skala, Arkysai, and Koksu.
- The Fifth Group: It contains the industrial Kokzhon phosphorite ore, including the Zhanatas and Gimmelfarb deposits.

This structured classification facilitates an efficient management of extraction and processing activities, ensuring the optimal utilization of resources in the Karatau phosphate basin. The phosphorites of the Karatau phosphorite basin consist of phosphorite grains and oolites. The grains are coarse, ranging from 0.07 to 0.3 mm, while the oolites are slightly larger, ranging from 0.05 to 0.4 mm. The primary phosphate mineral present in the basin is fluorapatite. Karatau phosphorites are located within the Sholaktau Svita of the Lower Cambrian period.[35]

The phosphorite deposits in this formation occur in a stratigraphic sequence from bottom to top, as follows:

- Dolomite Layer: This layer is composed of fine-grained dolomite, and has a thickness of 6–8 m.
- Siliceous Layer: This layer is 15–25 m thick and contains 70%–90% silicon minerals.
- Ore-rock Layer: Comprising several sub-layers of phosphorite, phosphorite-siliceous, and phosphorite-limestone-siliceous materials, this layer has a total thickness of 60 m, with the phosphorite layers themselves measuring 30–35 m.[36,37]

Currently, phosphate rock from Karatau is widely used in various sectors of the chemical industry in Kazakhstan and internationally. It is a key raw material for producing mineral fertilizers, elemental phosphorus, and other essential substances for the national economy.[38] In terms of reserves and quality, Karatau phosphate rock ranks among the world's leading deposits, with a phosphoric anhydride ($P_2O_5$) content of 27%–37%.[39]

This detailed classification of the geological structure and high quality of Karatau phosphorites underscores their importance in the global phosphate industry, particularly in supporting chemical and agricultural applications.

### 2.2 Monitoring of atmospheric air quality

The assessment of atmospheric air quality in the single-industry town of Karatau was based on data obtained from Automatic Station No. 1 of the Karatau branch of RSE 'Kazgidromet' in the Zhambyl region of the Republic of Kazakhstan. The monitoring station is located at 130 Tamdy Aulie Street, Karatau. The meteorological station, providing supplementary data, is situated in the city of Taraz (Fig. 2). In Karatau, two primary indicators are measured: (1) sulfur dioxide ($SO_2$) and (2) hydrogen sulfide ($H_2S$). Sampling is conducted continuously at 20-minute intervals. This section evaluates deviations from the maximum permissible concentration (MPC) for both the average concentration and the maximum single concentration of ambient air pollutants in Karatau. Additionally, the standard index (SI) and gross regional (GR) values of hydrogen sulfide in Karatau's atmospheric air were analyzed and compared. The document 'Hygienic Standard of Atmospheric Air in Urban and Rural Settlements' is taken as a basis for assessing the degree of atmospheric pollution index (Table 1).[40]

### 2.3 Determination of surface water quality

Surface water quality in the Talas district was monitored at two water bodies, *i.e.*, the Talas and Assy rivers, across six sampling sites (Fig. 3). Various physicochemical indicators of

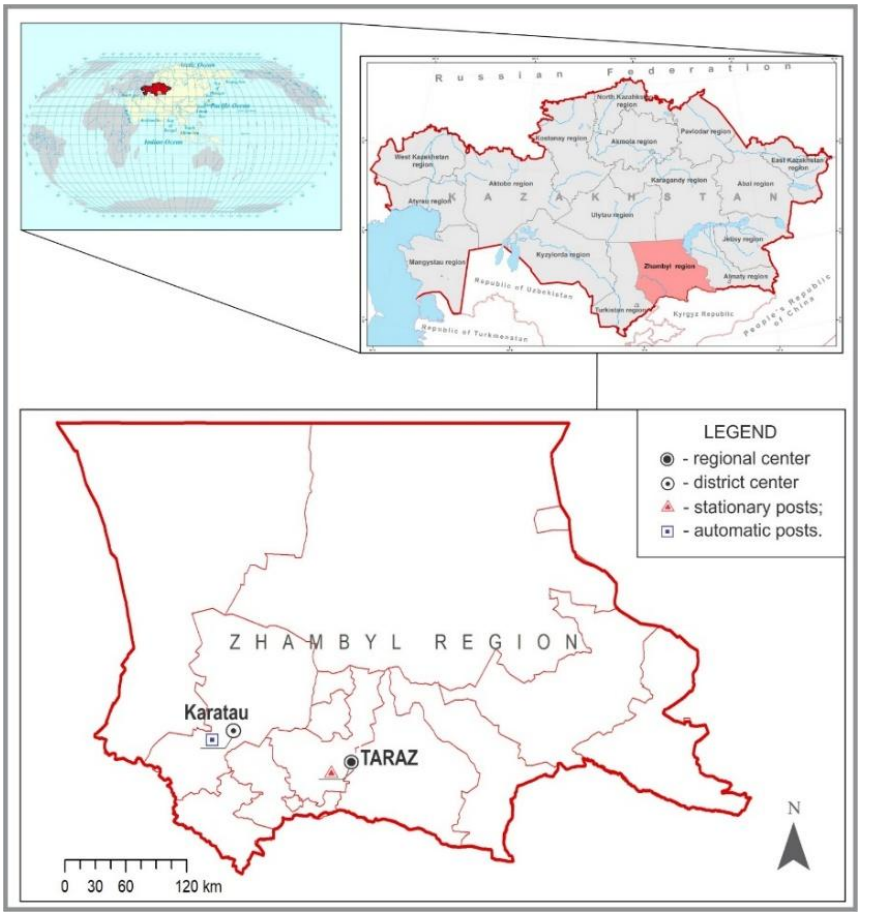



**Fig. 2:** Location of the observation point and weather station. Note: Compiled by authors.

**Table 1:** Estimation of the degree of atmospheric pollution index.

| Gradation | Pollution | Indicators | Monthly estimate |
|---|---|---|---|
| I | Low | SI | 0-1 |
| | | GR,% | 0 |
| II | Elevated | SI | 2-4 |
| | | GR,% | 1-19 |
| III | High | SI | 5-10 |
| | | GR,% | 20-49 |
| IV | Very high | SI | ›10 |
| | | GR,% | ›50 |

water quality were analyzed from the collected surface water samples. This analysis is particularly important because the waters of the Talas and Assy rivers are used for pasture irrigation, livestock watering, and as a water source for industrial production.

### 2.4 Determination of heavy metals content in soil and water

The content of heavy metals, including Pb, Cu, Cd, and Zn, in five soil and six water samples from the Karatau phosphorite basin was determined using the atomic absorption method. Atomic absorption spectrometry (AAS) measures the qualitative and quantitative composition of elements based on the absorption of light by free atoms.[41,42] The detection of heavy metals in soil was performed using an AA-6200 atomic absorption spectrophotometer (Shimadzu, Japan).

Soil samples were collected from five locations, with each location sampled at a distance of 30 meters from the designated point. The sampling sites included five study areas (Fig. 3B):

1. Abandoned waste site of Kazphosphate LLP: Soil sampled at a distance of 2 m from the waste, located in the northwest of the city (one sample).
2. City center intersection: Soil collected at the intersection of Kunayeva and Kachesova streets is approximately 3 km from Kazphosphate LLP (one sample).

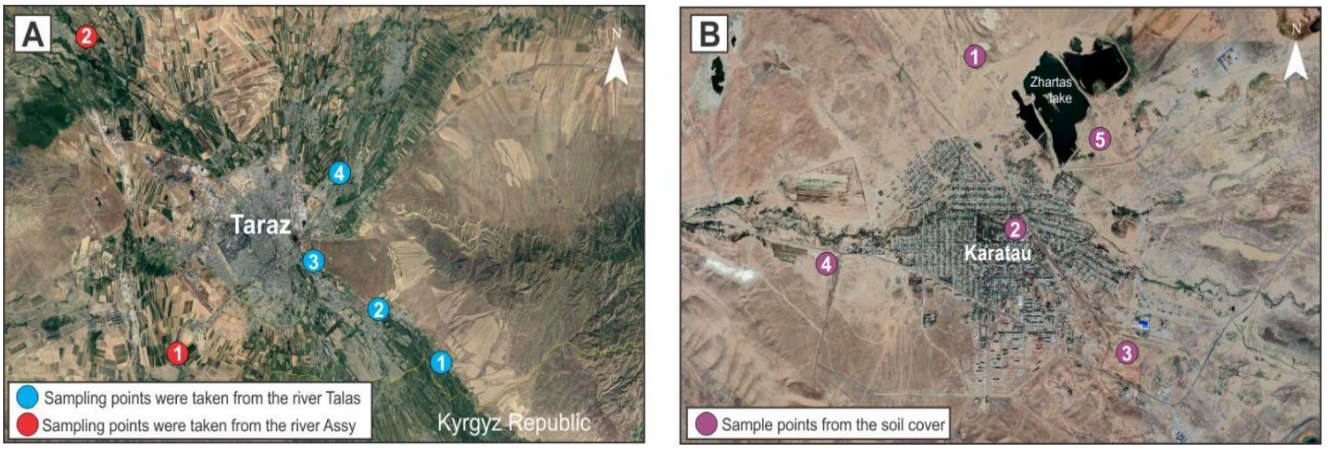



**Fig. 3:** Water and soil sampling locations: (A) Sampled sites on the Talas and Assy rivers; and (B) Places where soil samples were taken. The distance between the sampling sites is defined in the main text. Note: Compiled by the authors on the basis of Google Earth Engine data.

3. Residual storage area: Soil sampled in the southeast of the city is 1.4 km from Kazphosphate LLP (one sample).
4. Urban motorway suburb: Soil collected near the motorway on the western outskirts of the city is 1.6 km from Kazphosphate LLP (one sample).
5. Southeastern shore of Lake Zhartas: Soil is sampled 0.8 km from Kazphosphate LLP (one sample).

The soil samples were thoroughly cleaned of foreign inclusions such as stones, glass, and roots, then stirred and moistened with distilled water. Subsequently, 15 mL of concentrated nitric acid was added, and the mixture was heated until the sample was fully dissolved. The solution was then evaporated to a volume of 2.5 mL. Afterward, 5–10 mL of distilled water was added, and the mixture was reheated until the salts dissolved. The resulting solution was filtered using a Millipore filter with a 0.45-micron pore size.

For the determination of heavy metals by the atomic absorption method, ultra-sensitive wavelengths of linear resonance absorption were used for each element: Zn (213.9 nm), Pb (283.3 or 217.0 nm), Cu (324.7 nm), and Cd (228.8 nm). The concentration of metals in the soil (C), expressed in mg/kg, was calculated using Equation (1).[43]

$$C = \frac{a \times V_m}{b \times V_e} \quad (1)$$

where $a$ is the amount of detected metal by the hummingbird graph (μg/cm), $V_m$ is the total volume of mineralisate (cm3), $V_e$ is the volume of mineralisate applied for examination (cm3), and $b$ is the weight of the used soil (g).

The soils of industrial dumps were studied in comparison with the soils of natural, undisturbed land in the same area D1, D2, D3 – Anthrosols. These are soils sampled from locations where, after more than 50 years of accumulation on the surface of industrial dumps, new soils have formed from underground rocks that were collected in piles. Over time, plants have begun to naturally grow in these areas.

B1 is a natural soil that has not been subjected to human-induced degradation, located far from any industrial activity or dumpsites. The soil profile was classified into horizons, or layers, based on several characteristics, including the soil color, the amount of organic matter, the distribution and concentration of plant roots, soil density, moisture, structure, granulometric composition, and rockiness.

A1 is the top layer of mineral soil, rich in organic content and biological activity. The soil in this horizon typically exhibits darker colors due to higher organic material. The A1 horizon is the humus-accumulating layer, containing up to 15% organic matter by weight. A2 is a leaching horizon that forms beneath the A1 horizon. It is generally lighter in color, with a lower clay content, and a gradual decrease in organic matter. A3 is a transition horizon between the A and B horizons. This layer is lighter in color, with a noticeable reduction in organic matter, and properties of either the A1 or A2 horizons may prevail.

Bw Layer is a soil layer with weakly developed structure, indicating that soil development is in its early stages or disturbed conditions are present. For R & A1, in this horizon, the properties of the A1 layer are mixed with a high-hardness, dense rock horizon. Organic layers are also present, indicating interaction between soil and bedrock materials. For R & A2, similar to the R & A1 horizon, but the properties of the A2 horizon prevail. The layer exhibits high stone density and a more compact, less fertile organic layer. For B, the transitional horizon is enriched with both mineral and organic compounds. This layer represents the gradual shift from the more fertile topsoil layers to the less developed soil beneath. For C (Parent Rock), the layer of parent rock is the unweathered bedrock or the primary material from which the soil forms. It lies below all other soil horizons and typically exhibits a light orange color. This layer is the foundation for soil formation processes. Water samples were collected from each of the six named river sites, with one liter of water being taken per site into clean containers pre-treated with nitric acid. The water samples were filtered using filter paper and transferred to heat-resistant glass jars. Each sample was heated until the dry residue remained. To the dry residue, 10 mL of hydrochloric acid and 5 mL of

nitric acid were added, and the sample was heated again. The heating was first conducted at a temperature of 100–110 °C, then boiled down to form wet salts. Finally, the salts were dissolved with 15 mL of distilled water to prepare the samples for further analysis.

The main normative document for assessing the water quality of water bodies in the Republic of Kazakhstan is the 'Unified system of classification of water quality in water bodies' (Table 2).

**Table 2:** Surface water quality assessment class in the Republic of Kazakhstan.

| Class | Water quality assessment |
|---|---|
| 1 class (best quality) | - Water is suitable for all types of water use. |
| 2 class | - Water is suitable for fish farming, recreation, irrigation, and industry.<br>- Only for domestic drinking water supply, a simple water treatment method is required. |
| 3 class | - Water is suitable for recreation, irrigation, and industry.<br>- Water is suitable for breeding carp fish species; undesirable for salmonids.<br>- Conventional and intensive water treatment methods are required for the domestic drinking water supply. |
| >3 class | - Water is suitable for irrigation and industry. |
| 4 class | - Water is suitable for irrigation and industry.<br>- Deep water treatment methods are required for the domestic drinking water supply. |
| 4 class (worst quality) | - Water is only suitable for some industries hydropower, mining, and hydrotransportation. |
| >5 class | - Water is not suitable for all water uses. |

## 3. Results and discussion

### 3.1 Atmospheric air quality in the single-industry town of Karatau

The study results, based on data from the observation network, indicate that atmospheric air pollution levels in Karatau are low. Hydrogen sulfide pollution was recorded with a standard index (SI) value of 0.9 (low) and a gross regional (GR) value of 0% (low).[44] Both the average and maximum concentrations of pollutants remained below the maximum permissible concentration (MPC). The actual values are summarized in Table 3.

Table 3 presents atmospheric air pollution data for the Zhambyl Region, derived from the 2023 environmental information bulletin. The table compares daily average concentrations, maximum concentrations, and GR% (gross regional exceedance) for two key pollutants: sulfur dioxide ($SO_2$) and hydrogen sulfide ($H_2S$). It also lists the MPCs established by the WHO for both pollutants. The daily average concentration of $SO_2$ is 0.018 mg/m³, with a maximum of 0.027 mg/m³. These values comply with the WHO limit of 0.020 mg/m³ for daily exposure. The GR% indicator shows zero exceedance, suggesting no significant $SO_2$-related air quality issues in the monitored region. Similarly, the daily average concentration of $H_2S$ is 0.003 mg/m³, with a maximum of 0.007 mg/m³. Both values are within the WHO limit of 0.008 mg/m³, and the GR% indicator remains zero, indicating full compliance with the international air quality standards.

Recent years have shown a decreasing trend in air pollution levels. In 2020, 2021, and 2023, pollution levels were low, whereas in 2019 and 2022, elevated levels were recorded (Table 4). Notably, $H_2S$ displayed increased SI values during high-pollution years, reflecting heightened concentrations of this compound. $H_2S$ is produced primarily through the bacterial decomposition of organic matter, including human and animal waste. It is often emitted from sources such as sewage treatment plants, landfills, and wastewater systems, and is also formed during the breakdown of proteins.[45]

The data in Table 4 highlights the downward trend in overall air pollution levels in Karatau. The table shows a consistent decrease in the Air Pollution Index (SI and GR) from 2019 to 2023. In 2019, the SI was 1.9, whereas by 2023, it had been reduced to 0.9, indicating a significant reduction in pollutant concentrations over time. Similarly, the corresponding values for the GR index also show a decline, further underscoring the overall improvement in air quality. Several factors have contributed to this positive trend in pollution reduction. A key factor is the reduction in industrial production, which has likely resulted in fewer emissions. Additionally, stricter governmental environmental regulations and air pollution standards have played a critical role in driving this change. The effective implementation of these regulations, combined with growing local community activism and public pressure, has further supported improvements in air quality. Moreover, the adoption of more sustainable production practices and advanced technologies by industries in the region has likely mitigated the environmental impact and contributed to the observed improvements.

**Table 3:** Atmospheric air pollution data.

| Impurity | Daily average concentration (mg/m³) | Maximum concentration (mg/m³) | GR, % | MPC by the World Health Organization (WHO) (mg/m³) |
|---|---|---|---|---|
| Sulfur dioxide | 0.018 | 0.027 | 0.00 | 0.020 |
| Hydrogen sulfide | 0.003 | 0.007 | 0.00 | 0.008 |

Note: The table was compiled by the authors based on the 2023 information bulletin on the state of the environment in the Zhambyl Region.[44]

**Table 4:** Level of atmospheric air pollution (2019–2023).

| Air pollution index, % | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|
| SI | 1.9 | 0.8 | 0.9 | 1.3 | 0.9 |
| GR | 4.0 | 0.8 | 0.0 | 1.0 | 0.0 |

Note: The table was compiled by the authors based on the information bulletin on the state of the environment in the Zhambyl Region, 2019–2023.

### 3.2 Surface water quality in the Tala district

According to the unified classification system for water quality in water bodies of the Republic of Kazakhstan, the water quality concentration in the Talas River was recorded at 51.8. In 2023, the water quality of the Assy River was categorized as Class 3, indicating moderate pollution levels (Table 5).[44]

Table 5 indicates that, compared to January 2022, the quality class of surface water in the Talas River remained unchanged. The primary pollutants in the water bodies of the Talas district include magnesium, sulfates, and suspended solids. Notably, in January 2023, no instances of high or very high pollution levels were recorded in the Talas district. Detailed information on surface water quality is provided in Table 6.

**Table 5:** Water quality of the Talas and Assy rivers based on unified classification.

| Name of the water body | Water quality class | | Parameters | Concentration ($mg/dm^3$) |
|---|---|---|---|---|
| | January 2022 | January 2023 | | |
| Talas River | not standardized (>5 class) | not standardized (>5 class) | Suspended solids | 51.8 |
| Assy River | not standardized (>5 class) | 3 class | Magnesium | 27.7 |

**Table 6:** Surface water quality in the Talas district (Water extract in g/L).

| No. | Water body and object of study | pH | Composition of river water | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total salts (g/L) | Alkalinity | | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ | $K^+$ |
| | | | | Total in $HCO_3^-$ | From normal carbonates to $CO_3^{2-}$ | | | | | | |
| | Talas River | | | | | | | | | | |
| 1 | Zhasorken village, 0.7 km upstream | 8.57 | 1.657 | 0.537 | 0.034 | 0.071 | 0.632 | 0.083 | 0.141 | 0.186 | 0.007 |
| 2 | Solnechny village, 0.5 km below the gauging station | 8.57 | 1.169 | 0.381 | 0.005 | 0.064 | 0.433 | 0.074 | 0.101 | 0.114 | 0.003 |
| 3 | Taraz city, 7.5 km upstream and 0.7 km upstream of GRES wastewater discharge | 8.45 | 1.640 | 0.312 | 0.014 | 0.173 | 0.688 | 0.102 | 0.090 | 0.269 | 0.006 |
| 4 | Taraz city, 10 km downstream and 0.7 km downstream of collector-drainage water outlets from filtration fields of sugar and alcohol factories. | 8.25 | 1.675 | 0.0312 | 0.005 | 0.173 | 0.711 | 0.120 | 0.084 | 0.269 | 0.006 |
| | Assy River | | | | | | | | | | |
| 5 | Outskirts of Sholdala microdistrict, Kumshagal village district (near the bridge) | 8.03 | 1.128 | 0.127 | | 0.097 | 0.588 | 0.093 | 0.073 | 0.144 | 0.006 |
| 6 | Assy River, 500 meters below the village of Asa | 8.24 | 2.792 | 0.381 | 0.005 | 0.356 | 1.242 | 0.222 | 0.141 | 0.444 | 0.006 |

**Table 7:** Release of pollutants into the air by Kazphosphate LLP, tons (2019–2023).

| Pollutants | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|
| Total | 79.965 | 330.804 | 517.317 | 51.074 | 25.526 |
| Solid particles | 35.946 | 174.431 | 247.893 | 10.264 | 22.156 |
| Sulphur oxides | 15.17 | 61.432 | 147.523 | 0.003 | 1.055 |
| Nitric acid | 0.969 | 0.581 | 1.039 | 0.631 | 1.820 |
| Carbon monoxide | 7.11 | 24.257 | 22.415 | 1.1231 | 0.426 |
| Ammonia | 14.37 | 40.365 | - | 34.849 | - |
| The others | 6.4 | 29.738 | 98.447 | 4.204 | 0.069 |

Note: The table is based on data from the National Bureau of Statistics (2019–2023).[47]

**Table 8:** Water usage levels of major production enterprises within Kazphosphate LLP.

| Name of enterprises | Volume of water used: million $m^3$ /year | | | | |
|---|---|---|---|---|---|
| | 2019 | 2020 | 2021 | 2022 | 2023 |
| Zhambyl branch of Kazphosphate LLP (Novodzhambul Phosphorus Plant) | 5.4 | 4.49 | 3.26 | 4.8 | 7.26 |
| Taraz Mineral Fertilisers Branch of Kazphosphate LLP | 5.59 | 4.09 | 3.82 | 4.04 | 4.06 |
| Mining and processing complex "Karatau" branch of Kazphosphate LLP | 2.18 | 2.39 | 1.58 | 1.26 | 1.19 |

The study revealed that the Talas River, which flows through small towns in the Zhambyl Oblast, has a salt content ranging from 1.169 to 1.675, while the Assy River recorded the highest salt content at 2.792. In terms of pH levels, the Talas River ranged from 8.25 to 8.57, whereas the Assy River ranged from 8.03 to 8.24. These results indicate that both rivers are polluted by effluents from phosphorus plants.

### 3.3 Harmful wastes entering the atmosphere and hydrosphere

The chemical production facilities of Kazphosphate LLP are the primary sources of air pollution, contributing 19% of the total waste emissions.[46] In general, air pollution caused by certain wastes, such as dust, hydrogen fluoride, and ammonia, has shown a decreasing trend. Nitrogen dioxide and carbon monoxide levels have also been stabilized to varying degrees. The detailed indicators of pollutant content in the air are provided in Table 7.

In Karatau, the issue of wastewater treatment and utilization has been actively addressed. Domestic and industrial wastewater is processed in biological purifiers and collected in catchment areas, with a portion of the treated water being repurposed for agricultural needs. In recent years, the volume of water consumed by Karatau's phosfate rock production facilities have shown an annual increase (Table 8). Wastewater treatment challenges are particularly pronounced at the central site. The sewerage system is divided into two production zones: North-East and North-West. Wastewater from the North-East production zone is discharged into a filtration steppe covering 141 hectares in the village of Kumjota, located in the Baizak district, as well as on lands belonging to the inter-district special farm association in the Zhambyl region. More than 80% of domestic and industrial wastewater, amounting to 80–90 $km^3$ annually, is delivered to the filtration step within the Kuibyshev Production Cooperative territory in the Zhambyl region, which spans an area of 192 hectares. However, due to the absence of adequate treatment facilities at the enterprises, wastewater is transported to these filtration areas by gravity, often exceeding capacity. This has resulted in a significant technogenic impact on the geo-ecological environment of the entire Talas and Assy river valleys.

### 3.4 Heavy metals in soil and water

The study on heavy metal content in soil samples from the single-industry town of Karatau revealed high concentrations of zinc (99.6–654.4 mg/kg) and low concentrations of copper (19.9–24.0 mg/kg) (Table 9). In some areas, lead levels exceeded the MPC by 1–1.5 times. Copper content in the soil, ranging from 19.9–24.0 mg/kg, remains below critical thresholds and is not considered very high. The maximum zinc concentration, 654.4 mg/kg, was recorded in soil samples from the residual storage site, which is 12 times higher than the MPC. Additionally, soil samples taken near the ore residue (2 m) and along the city route showed zinc concentrations 7 times higher than the MPC. Plants and crops grown in such contaminated soil pose significant risks, as animals consuming these plants may be poisoned, negatively impacting human health through the food chain. Heavy metals such as Cd and Zn are particularly harmful, as they can cause kidney damage, gastrointestinal disorders, and respiratory cancers. Zinc toxicity also suppresses the growth of beneficial soil microorganisms, disrupts nutrient cycling, reduces soil fertility, and ultimately affects agricultural productivity and food security.

The concentrations of heavy metals obtained in water samples were below the MPC. The concentrations of heavy metals in water are presented in Table 10.

**Table 9:** Heavy metal content in soil.

| zPoint / heavy metals (mg/kg) | Pb | Cd | Cu | Zn |
|---|---|---|---|---|
| South-eastern shore of Lake Zhartas | 17.8+1.7 | 0.2+0.02 | 23.0+2.2 | - |
| From soil within 2 metres of the ore waste from the plant | 34.3+3.2 | 1.31+0.1 | 22.5+2.1 | 361.4+35.8 |
| Residual storage (Area in the south-east of the city) | 19.4+1.3 | 1.4+0.12 | 24.0+2.2 | 654.4+64.3 |
| City Centre intersection of Kunayeva and Kachesova streets | 33.9+2.9 | 2.1+0.2 | 19.9+1.7 | 99.6+8.9 |
| Urban motorway suburbs (Near the motorway on the right-hand West) | 27.0+2.0 | 2.2+0.2 | 20.0+2.1 | 384.9+34.4 |
| MPC (mg/kg) | 32.0 | 1.0 | 55.0 | 70.0 |

**Table 10:** Heavy metals in surface waters.

| Point / heavy metals (mg/L) | Pb | Cd | Cu | Zn |
|---|---|---|---|---|
| Talas River | 0.003+0.0002 | 0.0013+0.0001 | 0.09+0.008 | 1.81+0.1 |
| Assy River | 0.01+0.001 | 0.004+0.0003 | 1.05+0.1 | 2.7+ 0.2 |
| MPC (mg/L) | 0.03 | 0.005 | 3.00 | 5.00 |

### 3.5 Analysis of soil conditions in industrial dumps of phosphorite deposits

The study determined that primary soil formation processes are occurring in the technogenic dump of Karatau. These processes are influenced by factors such as rocks, vegetation, climate, relief, time, and anthropogenic activities, which collectively affect the soil-forming characteristics of the layers, structure, composition, and properties of young soils. Chemical analysis of soil gravel in the study area revealed that the humus content was higher in the upper layers (6 –7 cm) compared to the lower layers of the young soil formations in sites 2, 3, and 4. This observation indicates that the initial stages of soil degradation occur in a very thin layer of the embankment (Table 11).

Soil texture (clay content) ranges from 12.2 to 20.9 g/kg across different profiles and layers, with a higher clay content generally observed in deeper soil layers (e.g., D3: 18.5–20.9 g/kg). Calcium carbonate ($CaCO_3$) content varies between 6.20% and 12.7%. A noticeable decrease in $CaCO_3$ content is observed with increasing soil depth, particularly in profiles such as B1, where the surface layer contains 8.20%, dropping to 7.79% in deeper layers. The high $CaCO_3$ content in surface layers may indicate soil alkalinity. The soil pH in water ($H_2O$) is relatively consistent across all profiles, generally ranging from 7.0 to 8.5, indicating neutral to mildly alkaline conditions. The pH in calcium chloride ($CaCl_2$) is slightly lower than in water, reflecting the effect of $CaCl_2$ in reducing pH. This range suggests that the soils are neither highly acidic nor excessively alkaline.

**Table 11:** Physicochemical and agrochemical properties of soil-by-soil degradation processes.

| Soil profiles | Soil layers | Thickness (cm) | Clay (g kg$^{-1}$) | $CaCO_3$ % | pH | | N Total | N Mobile | $P_2O_5$ Total | $P_2O_5$ Mobile | $K_2O$ Total | $K_2O$ Mobile | Humus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $H_2O$ | $CaCl_2$ | % | mg/kg | % | mg/kg | % | mg/kg | % |
| B1 | A | 0-12 | 12.2 | 6.20 | 8.20 | 8.0 | 0.08 | 39.2 | 0.044 | 16 | 2.11 | 590 | 1.28 |
| | AB | 12-25 | 13.0 | 6.39 | 8.23 | 8.10 | 0.06 | 36.4 | 0.108 | 6 | 1.89 | 380 | 0.71 |
| | Bw | 25-46 | 12.6 | 7.48 | 8.25 | 8.14 | 0.04 | 33.6 | 0.108 | 6 | 1.78 | 300 | 0.51 |
| | 2C1 | 46-90 | 15.0 | 9.58 | 7.95 | 7.80 | 0.04 | 30.8 | 0.092 | 4 | 1.73 | 100 | 0.49 |
| | 2C2 | >90 | 13,9 | 7.73 | 7.79 | 7.61 | 0.03 | 22.4 | 0.072 | 3 | 1.89 | 80 | - |
| D1 | ^A | 0-6 | 15.6 | 8.57 | 7.58 | 7.23 | 0.04 | 33.6 | 0.204 | 10 | 1.83 | 200 | 0.71 |
| | ^R&A 1 | 6-17 | 16.7 | 12.7 | 8.20 | 8.12 | 0.03 | 28.0 | 0.172 | 3 | 1.44 | 80 | 0.17 |
| | ^R&A 2 | 17-30 | 12.2 | 7.54 | 8.50 | 8.27 | 0.03 | 28.0 | 0.204 | 3 | 1.38 | 80 | - |
| D2 | ^A1 | 0-7 | 13.0 | 7.10 | 8.56 | 8.32 | 0.07 | 22.4 | 0.324 | 25 | 1.61 | 210 | 0.86 |
| | ^A2 | 7-17 | 16.8 | 9.84 | 8.46 | 8.22 | 0.02 | 16.8 | 6.16 | - | 1.44 | 90 | 0.10 |
| | ^A3 | 17-32 | 14.7 | 8.31 | 8.28 | 8.10 | 0.02 | 14.0 | 0.380 | 2 | 1.25 | 70 | - |
| D3 | ^A1 | 0-2 | 18.5 | 12.20 | 8.13 | 8.00 | 0.06 | 30.8 | 0.288 | 20 | 1.44 | 200 | 0.88 |
| | ^A2 | 2-10 | 20.9 | 6.68 | 7.55 | 7.25 | 0.03 | 19.6 | 0.060 | 3 | 1.35 | 60 | 0.27 |
| | ^A3 | 10-31 | 17.9 | 11.8 | 7.58 | 7.36 | 0.03 | - | 0.084 | 3 | 1.25 | 50 | - |

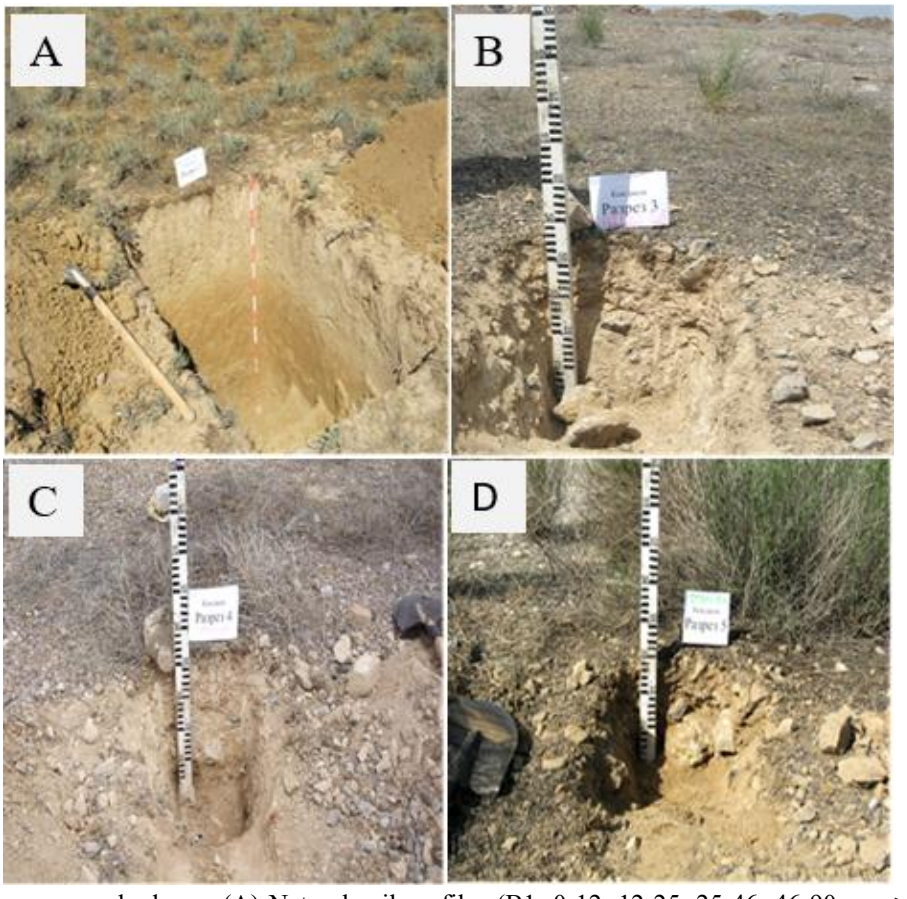



**Fig. 4:** Soil profiles in a man-made dump: (A) Natural soil profiles (B1: 0-12, 12-25, 25-46, 46-90 cm, >90 cm), (B) Anthrosol profiles (D1: 0-6, 6-17, 17-30 cm), (C) Anthrosol profiles (D2: 0-7, 7-17, 17-32 cm), and (D) Anthrosol profiles (D3: 0-2, 2-10, 10-31cm).

Phosphorus excessively alkaline. Phosphorus content is higher in the upper layers than in the lower ones. The phosphorus available for plant absorption is sufficient in most soil groups, promoting ecosystem recovery. However, the supply of exchangeable potassium varies, ranging from low to moderate levels in most samples. Nitrogen levels, however, are notably deficient in these soils.

Chemical analysis of the soil across different depths highlights several key trends:

- Humus content: Higher in the upper layers of young soils, with values ranging from 0.1% to 1.28%, suggests active degradation processes in thin rubble layers.
- Carbonate content: Influenced by phosforite ore, carbonate levels are elevated, particularly in the upper layers, playing a significant role in the soil formation.
- Macronutrient dynamics: Mobile phosforus is concentrated in the upper layers, while exchangeable potassium varies across samples. Nitrogen remains deficient, underscoring the challenge of restoring soil fertility in this human-altered environment.

The initial stages of soil formation in the dumps are characterized by sparse vegetation, limited root development, and weak mineralization of organic substances. Vegetation coverage ranges from 10% to 20%, while the soil profile typically consists of stony-gravelly or sandy layers with varying degrees of friability and carbonate deposits. These conditions demonstrate that soil formation on technologically disturbed lands at the Karatau deposit is slow and requires comprehensive restoration measures to support ecosystem recovery (Fig. 4).

Although the soil formation and remediation processes at the Karatau anthropogenic landfill are still in their early stages, there are evident signs of ecological stabilization. Over time, these young soils have the potential to develop into stable and productive systems through the gradual accumulation of organic matter, minerals, and nutrients. However, achieving full landscape restoration will require consistent efforts to mitigate the effects of past human activities and promote further soil development. The findings emphasize the importance of long-term monitoring and reclamation efforts to better understand and support the trajectory of soil regeneration in such disturbed environments. To further enhance the restoration efforts, modern technologies should be implemented in Karatau to decontaminate and reduce industrial waste in the phosfate rock massif. Specifically, waste generation can be minimized using advanced methods such as membrane filtration, bioleaching, and crystallization processes:

- Membrane Filtration Technology: This approach concentrates phosphate solutions and removes impurities

without requiring additional chemicals or reagents, making it both efficient and environmentally friendly.[48]

- Bioleaching: This method utilizes the metabolic activity of microorganisms to recover phosforus in an eco-friendly manner, while simultaneously reducing waste generation.[49]
- Crystallization Processes: Unlike the other two methods, crystallization can recover phosphorus directly from raw materials such as phosfate rock or phosphoric acid, without producing waste.[50,51]

The application of these technologies in phosphorus production offers significant potential to reduce the environmental impact of industrial activities, enhance sustainability, and improve overall production efficiency. However, the absence of programs or policies in Kazakhstan to adopt such advanced technologies poses challenges, particularly financial ones, for companies like Kazphosphate LLP. Establishing initiatives to implement these technologies will be critical for promoting environmentally responsible and sustainable phosphorus production in the region.

## 4. Conclusion

The sustainable development of the single-industry town of Karatau is closely tied to the environmentally responsible organization of phosphate production and management by Kazphosphate LLP. As one of the main employers in the region, Kazphosphate LLP plays a vital role in the local economy. However, the study highlights significant environmental challenges arising from phosphorus production, such as heavy metal pollution in soil, with zinc concentrations reaching up to 654.4 mg/kg and lead up to 34.3 mg/kg. Additionally, the reagents used for neutralizing toxic substances were found to be 1.5–2 times below planned levels. Zinc toxicity disrupts soil microorganisms, hampers nutrient cycling, and reduces soil fertility, thereby threatening agricultural productivity and food security. This contamination poses serious risks to human health, with the potential for kidney failure, gastrointestinal issues, and respiratory cancers among residents. To address these challenges, comprehensive measures are needed to restore the soil ecosystem in the technologically disturbed lands of the Karatau phosphorite basin. While the soil formation and reclamation processes at the Karatau landfill are still in their early stages, signs of environmental sustainability are emerging. Over time, young soils have the potential to become stable and productive through the gradual accumulation of organic matter, minerals, and nutrients. However, achieving full landscape restoration requires ongoing monitoring, attention to past anthropogenic impacts, and proactive reclamation efforts to support further soil development.

Key recommendations include: reclamation of abandoned quarries and waste dumps, reduction of dust emissions during phosphorus production, efficient treatment of industrial waste and wastewater, and reconstruction of the fluorine gas removal system to produce potassium fluoride. Additional measures involve constructing a water intake facility with a capacity of 500,000 cubic meters to separate clean and waste wastewater, protecting groundwater from contamination by chromium, chloride, and fluoride, organizing solid waste disposal sites, and expanding the production of construction materials using chemical waste. This study highlights the importance of implementing measures to mitigate air, water, and soil pollution from industrial and mining activities in Karatau. Understanding the distribution of phosphate waste and its impact on soil properties, microbial activity, and nutrient cycling will help reduce environmental harm and contribute to a circular economy by minimizing waste and conserving resources. Collaboration with environmental organizations and agencies will be critical to achieving these goals. Future research should evaluate the effectiveness of reclamation efforts in abandoned open pits and waste dumps in the Karatau phosphate basin to guide further restoration strategies.

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## Conflict of Interest

There is no conflict of interest.

## Supporting Information

Not applicable.

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