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Geocological problems in the development of non-metallic deposits in Kyrgyzstan

Introduction

The relevance of the study is determined by the need for sustainable development of Kyrgyzstan's mineral resource base in the context of increasing economic activity and international cooperation. It is important not only to use natural resources effectively but also to minimize the environmental risks associated with their development. The development of non-metallic deposits, being an important element of industrial growth, requires a comprehensive analysis accounting for the geocological consequences and modern approaches to rational subsoil use.

The Kyrgyz economy is showing positive dynamics in 2025. Under these conditions, mining and processing of mineral raw materials, especially non-metallic minerals, play an important role in industry. Kyrgyzstan actively cooperates with a number of countries,

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such as Kazakhstan, China, Türkiye, the United States, etc., which opens up new opportunities for trade and the introduction of innovative technologies in the mining industry. However, despite the positive economic prospects, the development of non-metallic deposits is accompanied by a number of geoecological problems that can substantially affect the state of the environment, public health, and ecosystem sustainability. As of 2025, the problem of developing non-metallic deposits in Kyrgyzstan remains insufficiently reviewed in the context of their impact on nature, which sets researchers the task of identifying key problems and developing effective methods to minimize them.

Theoretically, the issues of geoecology of non-metallic deposits have been investigated by a number of scientists. In the study by Djenbaev et al. (2024), radioecological work was conducted in the uranium natural-technogenic province of Min-Kush in Kyrgyzstan, including the analysis of gamma radiation, the content of radionuclides in tailings ponds and water, and an assessment of the radioecological situation after reclamation, which resulted in a map of the site. Rsetala et al. (2023) examined the bottom sediments of reservoirs used for recreational purposes in the Silesian Upland and its surroundings, and high concentrations of toxic elements such as lead, zinc, cadmium, chromium, strontium, and arsenic were detected, which confirms the contamination of sediments. Müller et al. (2025) reviewed the geological processes of formation of critically important metals, analyzed the problems and prospects of their exploration, and emphasized the importance of using advanced conceptual models for successful exploration in conditions of complex tectonics, hidden ore deposits, and limited resources. In an article by Syvyj et al. (2023) the issues of rational subsurface use in Ukraine were analyzed, including integrated field development, mining waste disposal, and optimization of the mineral resource base. An acute environmental problem of toxic waste accumulation was identified, and the need for state regulation and development of man-made deposits for the sustainable development of the country was underlined.

Pohl (2022) reviewed the current state and trends of metallogeny, analyzed its principles, classification of ore and mineral deposits, connection with geodynamic processes, and the use of metallogenic models in mineral exploration, stressing the importance of innovative methods and analysis of mineral systems for successful resource development in the face of growing demand for critically important metals. Groves et al. (2025) assessed the geological features and uneven distribution of critical metals needed for the transition to clean energy, along with the geopolitical and economic factors affecting their extraction and trade, stressing the need for global exploration and the development of a closed economy with a priority on resource processing. In the paper of Wu et al. (2022) an assessment of the quality of the ecological and geological environment (EEQ) in the area of intensive mining in the city of Tonghua was conducted using game theory, the method of analytical network process with coefficient of variation (ANP-CV) and analysis of geoinformation systems (GIS analysis), spatial patterns of EEQ degradation were identified, and measures for restoration were proposed and the protection of the ecological and geological environment, which can serve as a scientific basis for ecological construction and protection of the geological environment.

Saik et al. (2023) examined the conditions of extraction of deposits of magmatic and metamorphic origin for the production of crushed stone products in conditions of limited energy supply. Systematization of deposits was conducted, patterns of water flows into the quarry space were identified, and technical-technological solutions for processing raw materials were proposed. Kazmierczak and Górniak-Zimroz (2021) developed a methodology for assessing the environmental and social accessibility of key mineral deposits based on legal, environmental and planning constraints, classified 244 deposits in Poland into four accessibility classes, revealed that most deposits belong to classes III (accessible) and IV (inaccessible), and the exclusion of railway infrastructure from the analysis has increased the number of well- and very well-accessible deposits. Luo (2019) analyzed the problems of environmental pollution in metallurgical mining, highlighted its features, such as secrecy, late effects, diffusion, and accumulation of pollutants in catchment areas, which lead to serious damage to the environment.

These studies have disclosed the main problems and approaches to the development of deposits. However, in the field of phosphorite deposits and their impact on the ecology of Kyrgyzstan, research has not yet received adequate coverage. In addition, the issues of the production of mineral fertilizers, building materials such as cement, gypsum, lime, and their processing from local non-metallic resources remain poorly understood.

This study aims to evaluate the theoretical and economic aspects of the use of non-metallic resources of Kyrgyzstan, with an emphasis on the environmental consequences of mining and processing these minerals. The main objectives are to explore the possibilities of obtaining fertilizers and building materials from local non-metallic resources and the prospects for the development of phosphorite deposits, which can be an important step for the sustainable economic growth of the country and the development of agriculture.

1. Materials and methods

The study was conducted in eight seasonal stages (quarterly campaigns) between March 2023 and March 2025 to capture temporal and climatic variations. Fieldwork was carried out across 12 targeted mining sites in several regions of the Kyrgyz Republic, including the Chui Valley, the Issyk-Kul Valley, and the Osh and Jalal-Abad regions, which are highlighted on the map below (Figure 1).

The choice of these territories was determined by highly concentrated deposits of non-metallic minerals, which are actively used in construction and cement production. These regions represent key areas of the country's mining industry and are representative of assessing the impact of these activities on the ecosystem and socio-economic situation.

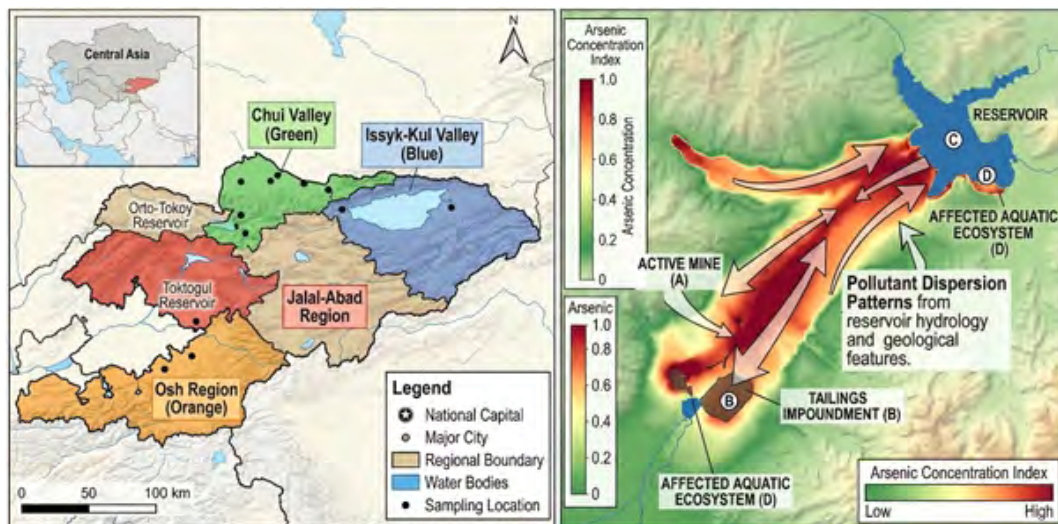


Fig. 1. Map of study areas and sampling locations in the Kyrgyz Republic

Rys. 1. Mapa obszarów badawczych i miejsc poboru próbek w Republice Kirgiskiej

Various methods and modern technical means were used to achieve the research objectives, including field work and the use of high-tech equipment. The field studies were conducted using portable environmental analyzers, which allowed measuring the concentration of dust in the atmospheric air and assessing the pollution of water resources near quarries. As part of the field work, portable Temtop M2000C and Aeroqual Series 500 analyzers were used to assess atmospheric air pollution, which measured dust concentrations of PM_{2.5} and PM₁₀, in addition to ozone and nitrogen dioxide. The measurements were conducted near quarries, on the border of settlements, and in remote areas. Dust measurements were conducted systematically at 36 observation stations distributed across the 12 selected mining sites. At each site, data were collected at three key points: directly at the quarries, on the border of settlements, and in remote control areas (at a distance of 2 km), which allowed identifying changes in the concentration of pollutants depending on the distance from the sources of pollution. During each of the eight quarterly campaigns, air quality was measured twice daily (morning and evening) over a three-day period at each station, resulting in a total of 1,728 discrete dust concentration measurements (PM_{2.5} and PM₁₀) over the course of the study. Water samples were taken from 24 established control points on rivers and lakes located in the immediate vicinity of the monitored mining facilities to analyze the quality of water resources. Sampling was conducted once per quarter at each of the 24 points during the eight field campaigns, yielding a total of 192 independent water samples. Water samples were taken in accordance with the GOST 17.1.5.01-80 methodology (2002) – a regional framework whose core sampling and preservation protocols are methodologically comparable to current international standards, such as ISO 5667-1:2023 (2023) and ASTM D3370 (2019). Initial

field assessments of water pollution were conducted using portable environmental analyzers. For detailed laboratory evaluation, the samples were specifically examined for pH, electrical conductivity, relevant ions (such as bicarbonates), and target heavy metals, predominantly arsenic, iron, and titanium. The quantitative analysis of trace heavy metals was performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), while ion concentrations were determined via Ion Chromatography (IC).

Satellite imagery and geographic information systems (GIS), namely Landsat, Sentinel-2, and QGIS (Quantum GIS), were used to assess the state of land resources. Using these technologies, changes in landscape characteristics were monitored along with a quantitative assessment of the extent of land degradation in the mining areas. GIS technology has allowed for a detailed cartographic analysis, revealing trends in land use and ecosystem processes related to the extraction of non-metallic minerals.

The research methodology included field research, repeated environmental measurements, and GIS-based spatial analysis of the collected data. This enabled both identifying key environmental problems such as air pollution, water resources, land and soil degradation, and assessment of their impact on the health of local communities dependent on these resources. The results of the study provide valuable data for the development of effective recommendations for minimizing environmental risks, introducing environmentally friendly technologies, and ensuring sustainable environmental management in the mining regions of Kyrgyzstan. These recommendations can become the basis for the creation of an environmental policy aimed at preserving natural resources and increasing the sustainability of ecosystems in mining regions.

2. Results

Non-metallic minerals play a crucial role in the global economy and industry. They make up about 70% of mineral resources (Upaghyay 2025), which are used in a wide variety of fields, from construction and materials production to chemical, glass, and pharmaceutical industries. These minerals are distinguished by the fact that they do not contain metallic elements in their composition, but have unique physico-chemical properties that make them indispensable for creating a wide range of products. These properties include high fire resistance (for example, graphite and talc), chemical inertia (for quartz and kaolin), high abrasiveness (for corundum), optical characteristics (for fluorite and gypsum), and adsorption and ion exchange capacity (as in zeolites and bentonites).

Unlike metallic minerals, which are mined primarily for the purpose of extracting metals, non-metallic minerals are the basis for the production of building materials such as cement, gypsum, brick, and for the creation of refractory and thermal insulation materials (Upaghyay 2025). These substances ensure the strength and durability of structures and improve their operational characteristics. For example, clay is used to produce bricks and tiles, and gypsum is used to create building mortars and finishing materials.

Non-metallic minerals used as building materials are common in Kyrgyzstan in geological formations of various ages, from the Lower Proterozoic to modern Quaternary sediments. Non-metallic minerals used as building materials are widespread in Kyrgyzstan and play an important role in the development of the national economy. According to the World Bank (Renaud 2019), there are more than 200 enterprises in the country engaged in the extraction of 15 different types of non-metallic mineral resources, mainly used in the construction industry. These include sand, gravel, limestone, gypsum, building stone, and other materials indispensable in the construction of buildings, structures, and infrastructure facilities. In 2015, there was a substantial increase in the production of certain types of building materials: granite and sandstone increased by 109%, marble and limestone by 30%, and kaolin clays by 19%. These indicators indicate a high demand for local construction resources and confirm the existence of favorable conditions for the expansion of the extractive industry.

In addition, in 2022, Kyrgyzstan ranked fifth in the world in mercury production, which further emphasizes the diversity of the country's mineral resource base and its strategic importance on a global scale (Renaud 2025). However, the most economically profitable and practically valuable deposits are associated with Mesozoic and Cenozoic rocks, and to a lesser extent with Paleozoic complexes. The most substantial deposits include sandstones and quartz sands of the Mesozoic and Cenozoic, formed in the conditions of continental and marine sedimentation basins. In addition, non-metallic minerals are in demand in the chemical industry, where they serve as raw materials for the production of lime, soda, dyes, various chemical additives, and organic compounds. In the glass industry, they are necessary for the production of glass, porcelain, and ceramics, and are also used in the manufacture of cosmetics, pharmaceuticals, and even in the food industry.

Non-metallic fossils are diverse in their origin and chemical composition. Clay rocks are an important group of non-metallic minerals, which includes white clay (kaolin), mica, and asbestos. White clay, or kaolin ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$), is widely used in the production of porcelain, ceramics, and the paper industry. Mica ($\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$) is the main material in the manufacture of electrical insulation, and is also used in building materials such as plasters and paints. Asbestos ($\text{CaO} \cdot 3\text{MgO} \cdot 4\text{SiO}_2$) is used in the manufacture of refractory materials, insulating substances, and building materials because it has high temperature resistance and strength (Ali et al. 2021).

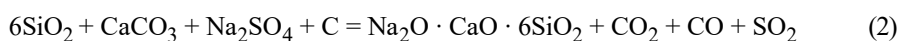
Carbonate rocks are a group that includes calcite, marble, chalk, limestone, magnesite, and dolomite, which are important in the construction and chemical industries. Calcite and marble (CaCO_3) are used in the production of building materials and decorative products such as cladding and countertops. Limestone and chalk (CaCO_3) are also used in the production of cement and lime, while magnesite (MgCO_3) and dolomite ($\text{CaCO}_3, \text{MgCO}_3$) are used for the manufacture of refractory materials. In nature, magnesite and dolomite can decompose under the influence of carbon dioxide (CO_2) from the air to form bicarbonates, which is also important for the formation of carbonate minerals and processes in soil ecology.

The chemical reaction in which magnesite and dolomite are exposed to CO_2 and water (Montes-Hernandez et al. 2020) can be represented as follows (1):



Siliceous rocks include feldspar, quartz, rhinestone, amethyst, agate, and other minerals that play a major role in the production of glass, porcelain, and refractory materials. Feldspar, represented by albite ($\text{NaAlSi}_3\text{O}_8$) and orthoclase (KAlSi_3O_8), is used in the ceramic and glass industries and the production of paint and varnish materials. Quartz and rhinestone (SiO_2) are widely used in the production of high-quality glass.

In addition, quartz is used as a desiccant in the pharmaceutical and chemical industries, for the production of silica in the refractory industry (Eshete 2020). Glass production using silica can be expressed by the following equation (2):



Quartz is an important component in the cement industry, where it is used as an additive to Portland cement, improving its strength characteristics and resistance to chemical influences. The presence of quartz in cement mixtures increases their durability, reduces shrinkage during solidification, and increases resistance to aggressive media (Rashad et al. 2022).

Quartz sand, in addition to its main component, silicon dioxide (SiO_2), may contain impurity minerals that affect its quality. Iron oxides (Fe_2O_3 , Fe_3O_4) give the raw material an undesirable color and change its chemical properties. Carbonates such as calcite (CaCO_3) and magnesite (MgCO_3) can cause defects in the final products, and clay minerals, including kaolinite and montmorillonite, degrade the strength characteristics of products, reducing their heat resistance and density. Notably, quartz sand and clay mining can have an immense impact on the environment, especially in areas with intensive production of building materials (Table 1).

In regions such as Chui and Osh, landscape changes, water pollution, and loss of biodiversity are observed. For example, erosion processes often occur in clay mining sites, which leads to the disruption of the soil structure and degradation of agricultural land. Geoecological consequences include the formation of quarries, which disrupt natural water exchange processes, pollution of rivers and lakes by dust particles, and chemicals released from rocks, in addition to changes in the hydrological regime of rivers and reservoirs, which affect local flora and fauna. The Chui region, where large sand deposits are concentrated, may suffer from pollution of rivers and streams associated with sand extraction and processing. The Osh region, where clay and sand-gravel mixtures are actively mined, is facing problems with groundwater pollution.

Quartz is widely used in the production of silicate bricks, but sand for these purposes must have strictly defined characteristics. The clay content in the sand should not exceed 5–6% since an excessive amount of clay particles impairs the adhesion of particles and reduces the strength of the finished material (Murali et al. 2024). In addition, sand should not contain organic impurities, as they can cause defects during heat treatment. In the production of fine

Table 1. The impact of mining on the environment in Kyrgyzstan
 Tabela 1. Wpływ górnictwa na środowisko w Kirgistanie

Mineral resources	Region	Type of environmental impact	Mitigation measures
Quartz sands	Chui region	River pollution, landscape destruction, soil erosion	Progressive technical reclamation with topsoil replacement (20–30 cm), installation of sedimentation ponds (retention time ≥ 48 h) for suspended solids removal, and riparian buffer zones (minimum width 15 m).
Clay rocks	Osh region	Pollution of water bodies, changes in the hydrological regime	Implementation of closed-loop water circulation systems ($\geq 85\%$ reuse efficiency), lined tailings storage facilities with leachate collection, and mechanical-chemical wastewater treatment (coagulation + filtration).
Phosphorites	Jalal-Abad region	Pollution of water sources, loss of biodiversity	Application of dust suppression systems (water spraying at $2\text{--}3\text{ L/m}^2$), installation of baghouse filters (PM removal efficiency $\geq 95\%$), and continuous air quality monitoring stations (PM _{2.5} , NO ₂ , O ₃) with hourly recording.
Peat	Issyk-Kul region	Ecosystem dehydration, water pollution	Hydrological regime restoration through controlled rewetting (groundwater level recovery to within 10–20 cm of surface), prohibition of drainage channels, and biodiversity recovery programs with native species reintroduction.
Glauconitis	Talas region	Soil pollution, ecosystem destruction	Soil remediation using phytoremediation (metal-accumulating plants such as <i>Brassica juncea</i>), application of organic amendments (biochar 2–5% w/w), and erosion control via geotextiles and slope terracing.

Source: compiled by the author based on Sabyrbekov and Overland (2021).

ceramics, quartz sand must contain at least 93% SiO₂, as a higher quartz content improves the quality of ceramic products. The proportion of iron (Fe₂O₃) and titanium (TiO₂) oxides should not exceed 0.3%, since their high content can lead to discoloration of products and a decrease in their strength. The presence of carbonates, particularly CaO, is limited to 2% since their excess worsens the heat resistance of materials (Xu et al. 2021). The size of the sand grains also plays an important role: the residue on the No. 4 sieve should be no more than 5%, which determines the grain size of the sand and its suitability for ceramic production.

The main share of these deposits is made up of clay rocks and sand-gravel mixtures, which are widely used in construction and the production of various building materials (Příkryl 2021). Clay raw materials are used for the manufacture of ceramic products, cladding materials, and bricks, while sands and sand-gravel mixtures are important components of concrete and road surfaces.

By the beginning of 2022, more than 200 deposits of construction raw materials had been explored and put into commercial operation in Kyrgyzstan, of which about 100 are already being developed (Kyrgyzstan 2022). The remaining deposits make up the reserve fund and can be used in the future, depending on the growing needs of the construction sector. The use of local resources helps reduce dependence on imported raw materials and develop the national production of building materials, which is especially important for the economic stability of the country.

As for 2025, large enterprises involved in the production of building materials are operating in Kyrgyzstan. Among them, there is one cement-slate plant and five cement plants that produce cement for construction and industry. In addition, factories for the production of wall building materials such as bricks, blocks, and panels operate in the country, among which the largest-scale are: Kant Cement and Slate Plant, Aravan Cement Plant, Tokmak Glass Plant “Interglass”, Southern Construction Materials Plant, Precast Concrete (reinforced concrete products) plant, and Bishkek Concrete Plant. There are also enterprises specializing in the production of products from natural building and facing stone used for exterior and interior decoration of buildings, among which, Asia Concrete and EKOL STORY are notable.

Due to the active development of the construction sector, there is a constant increase in demand for building materials and raw materials. In this direction, further examination of 369 of the most promising objects with high potential for industrial development, including sandstones and quartz sands of the Mesozoic and Cenozoic, limestone deposits, granite deposits, gypsum deposits, and clay shales and siltstones, is of particular importance. The discovery of new deposits of construction raw materials will strengthen the country's resource base, ensure an uninterrupted supply of necessary materials to construction enterprises, and support economic growth associated with the development of infrastructure and housing construction. Table 2 shows the main deposits of non-metallic minerals in Kyrgyzstan, which are widely used in construction, cement production, ceramic products, and other industrial sectors.

Table 2. The main deposits of non-metallic materials in Kyrgyzstan

Tabela 2. Główne złoża materiałów niemetalicznych w Kirgistanie

No.	Types of raw materials	Total number of objects	Main deposits
1	Natural building stones	168	Zhil-Arykskoye, Chui region; Aktash, Osh region
2	Natural facing and decorative facing stones	163	Arym, Jalal-Abad region; Kainda, Sary-Tash, Osh region
3	Carbonate rocks: including ♦ limestone for lime ♦ limestone for cement raw materials	36	Kurmentinskoye, Issyk-Kul region
4	Gypsum	133	Changyr-Tash, Jalal-Abad region; Naukatskoye, Osh region
5	Clay rocks (including clays and loams for construction and rough ceramics)	568 (392)	Ala-Archinskoye, Chui region; Tyuleiken, Osh region; Kurmentinskoye, Issyk-Kul region
6	Loams and clays as cement raw materials	13	Kurmentinskoye, Issyk-Kul region
7	Clay shales for the production of expanded clay	35	Bulteke (Ak-Suu), Chui region
8	Bentonite clays	12	Ivanovskoye, Chui region
9	Deposits of sand and gravel	315	Katta – Khazskoye, Tokmokskoye, Chui region
10	Building and silicate sands	71	Ivanovskoye, Chui region; Sary-Bulakskoye, Jalal-Abad region
11	Quartz sands and sandstones	48	Suluktinskoye, Batken region

Source: compiled by the author based on Östensson et al. (2023).

The extraction and processing of these materials have a substantial impact on the environment, leading to a number of geocological problems. Among them are the degradation of soil cover, disturbance of natural landscapes, pollution of surface and groundwater, and deterioration of air quality due to dust emissions (De Haes and Lucas 2024). Specifically, our field assessments yielded 1,728 discrete dust concentration measurements over the course of the study, capturing significant spatial variations in PM_{2.5} and PM₁₀ levels directly at the quarries compared to the remote control areas. For people, especially those living near quarries, constant exposure to dust can cause respiratory problems, including asthma, chronic bronchitis, and other lung diseases. Dust containing fine particles can enter the lungs and cause inflammation, impairing overall health. The risk of developing respiratory diseases increases immensely in children and the elderly. In addition, dust also has a devastating effect

on vegetation. Dust particles settle on the leaves and stems of plants, reducing their ability to photosynthesize and, as a result, slowing down their growth and development. This leads to a deterioration of soil quality and biological diversity in the ecosystems around the quarries.

Deposits, especially in areas where production is accompanied by the use of chemicals or waste, can substantially affect the quality of water sources. Pollution of rivers and lakes occurs for several reasons. One of them is the leaching of chemicals from rocks containing toxic components, such as ferruginous or titanium-containing minerals, which, when in contact with water, can lead to contamination of reservoirs. Pollution can also be caused by unauthorized discharge of wastewater in the mining area, which contributes to the ingress of pollutants into reservoirs. In addition, the process of processing materials, especially during the extraction of clay rocks, can be a source of contamination of water resources, since chemical residues formed during processing enter the water. These factors together can lead to serious deterioration of water quality in rivers and lakes, which negatively affects ecosystems and the health of local residents. Particularly noticeable changes are taking place in the following areas: Chui Valley, Issyk-Kul Valley, Osh, Jalal-Abad, and Batken regions, and the Toktogul district. Detailed laboratory evaluation of the 192 independent water samples, collected in strict alignment with international protocols such as ISO 5667-1:2023 and ASTM D3370, confirmed the presence of heavy metal contamination. Quantitative analysis via Inductively Coupled Plasma Mass Spectrometry (ICP-MS) explicitly detected elevated concentrations of arsenic, iron, and titanium leaching from local rocks. These empirical factors require careful monitoring and the development of measures to reduce the negative impact on the ecosystems of the region.

Extractive enterprises should actively implement measures for environmental control and sustainable use of natural resources to minimize the negative impact on the environment. One of these measures is land reclamation, which includes the restoration of ecosystems after the completion of mining. This may include planting vegetation, restoring aquatic ecosystems, and terracing slopes to prevent erosion. It is also important to use closed water supply cycles, which reduces pollution of water bodies since the water used in enterprises is cleaned and reused. Waste management is an equally important measure, which includes ensuring proper storage and disposal of chemical and other wastes, preventing them from entering reservoirs and soil. These measures will help maintain ecological balance and increase the sustainability of local ecosystems in conditions of intensive extraction of natural resources.

In addition to the above-mentioned non-metallic minerals, Kyrgyzstan also has substantial reserves of apatite, phosphorites, humic coal, glauconite, peat, and other mineral resources that are instrumental in the development of various industries and agriculture. When the demand for mineral fertilizers is constantly growing, even small deposits of these minerals become strategically important to provide the country with the necessary agrochemical resources (Kot-Niewiadomska et al. 2021).

The economy of Kyrgyzstan benefits from non-metallic deposits used for infrastructure construction and road building (Strazzabosco et al. 2022). Heavy extraction of non-metallic

resources degrades land, water, and air quality, harming ecosystems and local residents, the study found (Craik et al. 2022). Based on the repeated field measurements of PM_{2.5} and PM₁₀, water-quality sampling, and GIS-based spatial comparison of the monitored sites, the highest contamination risk was observed in the rivers and streams of the Chui region and in groundwater in the Osh region. These vulnerable zones were associated with elevated dust exposure and with local leaching from ferruginous and titanium-bearing rocks, as well as residues generated during clay processing. The spatial analysis was used to describe patterns of environmental vulnerability rather than to present a calibrated predictive dispersion model. Open-pit mining, especially landfills and groundwater regime alterations, destroys ecosystems, requiring sustainable natural resource management (Figure 2).

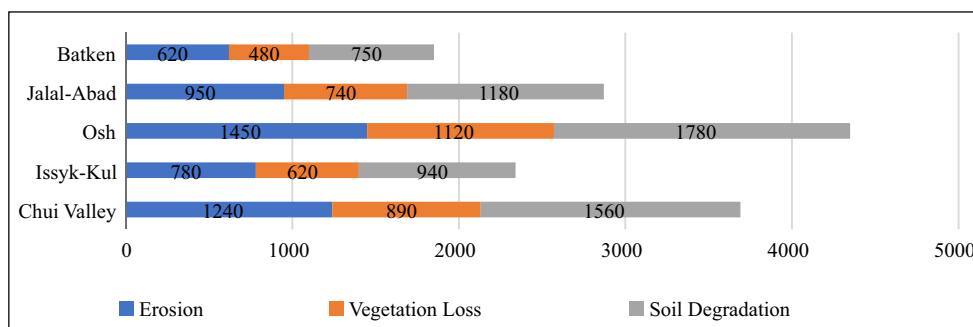


Fig. 2. Land degradation by region
Source: compiled by the author based on Gabriele et al. (2023)

Rys. 2. Degradacja gleby według regionu

Bioremediation and land reclamation could help reduce Kyrgyzstan's mining pollution. Bioremediation, which uses plants or microbes to remove toxins, is cost-effective and sustainable but requires time and specific conditions. Land reclamation, involving soil restoration and vegetation replanting, can slow land degradation but needs significant investment and long-term maintenance. Both methods require specialized knowledge and high initial costs, making them challenging to implement in large mining areas. Successful implementation will depend on continuous monitoring, funding, and strong regulatory oversight, alongside closed-loop water systems and environmental monitoring.

Kyrgyzstan is a predominantly agrarian country, and most of the population is directly or indirectly engaged in agriculture. Soil fertility and crop yields depend on the timely application of fertilizers, especially phosphorus and potash fertilizers, which improve soil structure, increase its fertility, and promote plant growth. However, the republic does not have its own fertilizer plants, and all products are imported from neighboring countries such as Uzbekistan and China (Abdulhamidov 2014). This both increases the cost of agricultural

products and creates dependence on external supplies, which, given the instability of global markets, may pose a threat to the state's food security.

In this regard, the development of phosphorite deposits, especially located in the southern regions of Kyrgyzstan, is one of the priorities for the development of the national economy. The creation of mineral fertilizer production will not only reduce import dependence but also create additional jobs, attract investment in the mining and chemical industries, and increase the competitiveness of local agricultural products in domestic and foreign markets (Anlauf 2023). Furthermore, the development of national fertilizer production will contribute to the stable provision of farmers with the necessary agrochemicals, which in the long term will have a positive impact on the development of agriculture and strengthen the food security of the country.

Enterprises engaged in mining and processing of minerals should pay special attention to the rational use of natural resources in their activities, as the mining industry has a strong impact on the environment (Ayuk et al. 2020). Effective management of natural resources helps to reduce environmental risks and also ensures the sustainable development of the economy, preserving the natural potential for future generations.

The rational use of natural resources is based on scientific-technological achievements, environmental principles, and high labor productivity. It is important to introduce advanced extraction and processing technologies aimed at reducing waste, increasing the recovery rate of useful components, and lowering the energy intensity of production.

Kyrgyzstan can draw on the experience of other countries to improve environmental control and ensure sustainable environmental management, building on successful national and international initiatives. As part of national efforts, specific legislation on environmental safety in the mining industry should be developed to establish strict requirements and control compliance with environmental standards; for example, a new regulation should be issued on the management of flotation waste for the operation of phosphate deposits. The introduction of environmental audits at mining enterprises will help to increase transparency and responsibility for environmental impacts. The implementation of environmentally friendly technologies in the extraction and processing of minerals can drastically reduce the negative impact on nature, ensuring a more sustainable use of resources.

International experience can also play a key role in improving environmental control. Australia is actively implementing innovative technologies in the mining industry, such as waste recycling systems and closed water supply cycles in mines. As a result of these measures, Australia has been able to considerably decrease water and soil pollution, improve ecosystem restoration, and overall mining efficiency (Strazzabosco et al. 2022).

Canada actively applies environmentally friendly technologies in oil and gas production, including the use of carbon dioxide to increase mineral extraction, which reduces carbon emissions and improves production efficiency (Craik et al. 2022). Furthermore, due to the introduction of more environmentally friendly waste recycling and disposal methods, the country has reduced the level of soil and water pollution in mining areas.

Sweden uses water recycling and purification technologies in the mining industry, which reduces water consumption and minimizes pollution of water resources. Several projects have been launched to introduce closed-circuit water circulation systems, which not only reduce the environmental impact but also bring economic benefits in the form of reduced operating costs (Söderholm et al. 2022).

In the Republic of South Africa, close attention is paid to technologies for restoring ecosystems after mining. The introduction of innovative methods of land reclamation, such as landscaping and soil restoration, enabled the successful restoration of ecosystems destroyed by mining operations (Carbutt and Kirkman 2022). It also contributed to improving the quality of life of local communities that had previously suffered from environmental problems. These examples show how the introduction of modern technologies and methods can greatly improve the environmental situation in the mining industry.

In addition, effective environmental management is closely linked to the social responsibility of enterprises. This includes measures for land reclamation, restoration of disturbed landscapes, protection of water resources, and implementation of environmental monitoring programs. Effective integration of environmental monitoring at all stages of mining and field development is vital to ensure sustainable development and minimize environmental damage. The introduction of various monitoring tools allows for monitoring changes in ecosystems and taking prompt measures to prevent negative consequences. One of these tools is remote sensing, which is used to monitor changes in the landscape and the state of ecosystems, allowing any disturbances such as erosion or soil degradation to be recorded (Gabriele et al. 2023). Geophysical surveys are used to assess the state of aquifers, helping to identify possible threats of water pollution. Environmental indicators and models are used to predict possible environmental impacts and determine how different types of activities may affect the environment in the future. In addition, air, water, and soil quality monitoring systems using sensors and gauges provide for the continuous monitoring of pollutants, which helps to respond quickly to pollution and prevent environmental disasters.

It is especially important to pay attention to the issue of land rehabilitation after the completion of mining, which is one of the main areas in the study. This process requires an integrated approach that includes several stages and activities. Vegetation restoration plays a crucial role, as it helps not only to restore biological diversity but also to strengthen the soil, preventing its erosion. Improving soil structure is also a fundamental aspect of rehabilitation, as it helps restore its fertility, improving conditions for plant growth and ecosystem restoration. Restoration of water resources is another essential stage since pollution of water bodies is one of the most serious environmental problems associated with mining (Murmu and Behera 2024). The application of measures to purify and restore aquatic ecosystems helps to return water resources to their natural state, which is of great importance for the local flora and fauna. Only an integrated and responsible approach to the exploitation of natural resources will ensure environmental safety, preserve public health, and support the sustainable development of natural and economic systems.

3. Discussion

The development of non-metallic deposits in Kyrgyzstan plays an important role in the country's economy by providing construction and road materials for infrastructure projects. However, as the study showed, intensive extraction of non-metallic resources causes substantial geocological problems, such as land degradation, pollution of water bodies, and deterioration of air quality, which negatively affect ecosystems and the health of local residents. This conclusion is directly supported by the 1,728 discrete dust concentration measurements of PM_{2.5} and PM₁₀ taken systematically at 36 observation stations, alongside the detailed laboratory evaluation of 192 independent water samples demonstrating the presence of target heavy metals, predominantly arsenic, iron, and titanium. Modeling of the spread of pollutants conducted during the study revealed specific regional vulnerabilities: water bodies in the Chui region and groundwater in the Osh region are at the highest risk of contamination (Mamrasulova and Orozakunova 2024). This pollutant spread modeling utilized the empirical data gathered from the 24 established control points, definitively identifying that the rivers and streams of the Chui region and the groundwater of the Osh region are the areas at the highest risk. The modeling indicated that pollutants such as ferruginous and titanium-containing minerals, alongside chemical residues from material processing, are actively leached into these specific water sources, which underscores the importance of an integrated approach to solving environmental problems. The results of the study also confirm that open-pit mining, in particular, the creation of landfills, and changes in the groundwater regime, immensely worsen the state of ecosystems, which requires the introduction of sustainable methods of natural resource management.

These problems become especially relevant with increasing production volumes, which require attention to environmental impacts and ensuring sustainable management of natural resources. Oğuz (2022) emphasizes that man-made changes, such as land degradation, are becoming a serious threat to the ecosystem and agriculture, especially in areas such as the Absheron Peninsula, where mining goes hand in hand with urbanization processes. Water pollution is another key environmental problem faced by the mining industry. During the processing of minerals, water can be polluted with chemicals and heavy metals, which reduces the quality of water resources and threatens the ecosystems of rivers and lakes. De Sa and Korinek (2021) focused on transportation and logistics issues, which also have an impact on the ecosystem, especially when transporting finished products. The impact on the landscape is also an important environmental issue related to the development of non-metallic deposits. Landscape change is also an important problem, as mining disrupts natural beauty and natural processes. Iannucci et al. (2022) stress the importance of preserving not only the ecological but also the aesthetic significance of the deposits. The authors demonstrate how the loss of natural landscapes and ecosystems can negatively affect the tourist attractiveness of the region and the quality of life of the local population.

A comparison of the conducted study with international literature reveals both shared patterns and context-specific deviations in the geocological impact of mining. While De Sa

and Korinek (2021) emphasize environmentally sound technologies for water and soil protection, and Oğuz (2022) highlights water pollution and soil degradation, the direct application of their proposed solutions requires careful adaptation. For instance, the previously discussed models from Australia, Canada, Sweden, and South Africa present excellent benchmarks; however, high-tech closed water supply cycles and carbon injection methods demand substantial capital investment, which is often a limiting factor for local mining enterprises in Kyrgyzstan. Furthermore, Kyrgyzstan's high-altitude mountainous terrain and arid climate make standard land rehabilitation practices challenging due to slow vegetation growth and high soil erosion rates.

Rather than merely listing universal environmental problems, comparing our field data with international benchmarks provides deeper insights. For example, the heavy metal leaching and dust concentrations (PM_{2.5} and PM₁₀) observed near the quarries in the Osh and Chui regions exhibited significantly higher seasonal variability than the values reported by Oğuz (2022) for the Absheron Peninsula. This discrepancy is primarily due to Kyrgyzstan's fragmented topography and sharp continental climate, which exacerbates wind erosion and rapid runoff during the snowmelt period.

To address these specific challenges, particularly the stabilization of non-metallic mining waste, low-cost but highly effective engineering solutions must be prioritized. While Mulligan et al. (2025) stress the importance of bioremediation and agronomic methods, physical and chemical stabilization of the tailings is a critical prerequisite. In this context, surface paste disposal techniques offer a highly applicable solution. As demonstrated in "The investigation of geochemical and geomechanical properties in surface paste disposal by pilot-scale tests" (Bascetin et al. 2022), adding binders like cement to tailings significantly reduces permeability and prevents the leaching of toxic elements into groundwater – a primary concern in the Jalal-Abad and Osh regions. Furthermore, to accommodate the limited financial resources of local enterprises, the findings from "Effects of pozzolanic materials in surface paste disposal by pilot-scale tests: observation of physical changes" (Bascetin et al. 2021) show that substituting cement with pozzolanic materials like fly ash can improve the volume compressibility coefficient and reduce binder costs by up to 50%. This substitution maintains sufficient resistance to sudden temperature changes and seasonal weathering, making it an economically and technically viable waste management strategy for Kyrgyzstan's specific geological conditions.

To prevent pollution of water bodies and the environment in general, it is necessary to use modern filtration and purification methods and practices to minimize emissions of pollutants into the atmosphere. Wei et al. (2024) concentrate on how the mining industry should integrate sustainable solutions to reduce its environmental footprint and promote sustainable development. For example, new technologies for processing mineral resources and waste management help to reduce the impact on water and air resources.

Mohammad et al. (2022) consider the possibilities of using electrokinetic methods in geotechnical and geoecological applications, such as cleaning contaminated soils and soil stabilization, which may be useful for places where non-metallic minerals are actively

mined. Special attention should be paid to the relationship between the production of non-metallic minerals and sustainable development. Wei et al. (2024) stress in their work that proper management of natural resources and the introduction of innovative technologies in the mining industry can greatly increase resilience to environmental challenges associated with this process. It is important that the extraction of non-metallic minerals is accompanied by measures to restore ecosystems and preserve natural resources for future generations.

Thus, to minimize geocological risks and ensure sustainable development in the mining regions of Kyrgyzstan, it is necessary to mandate specific modern, environmentally friendly technologies, such as making the use of closed-loop water systems mandatory in quartz sand mines in the Chui region. Additionally, improving targeted environmental monitoring systems and strengthening control over compliance with these new regional environmental standards is essential. In addition, it is important to continue research in the field of ecosystem restoration and the development of new methods for cleaning polluted reservoirs and lands.

Conclusions

As a result of the conducted examination of geocological problems related to mining activities in Kyrgyzstan, important results were obtained that confirm the substantial impact of such processes on the environment and public health. Based on comprehensive field research across 12 targeted mining sites over eight seasonal stages and mathematical modeling, it was established that open-pit mining, in particular, the construction of quarries and the creation of landfills, changes in the groundwater regime, lead to a deterioration in the quality of air, reservoirs, and lands. These structural findings are concretely backed by the quantitative analysis of trace heavy metals via Inductively Coupled Plasma Mass Spectrometry (ICP-MS) from field samples and the systematic air quality monitoring conducted throughout the study. This has a devastating impact on ecosystems, which hinders the sustainable development of these territories and requires the development of effective environmental protection measures.

One of the key results of the study was the identified dependence of atmospheric air pollution on the distance from pollution sources, which provides for a more accurate assessment of the risks to the health of the population living near mining enterprises. Modeling of water pollution demonstrated that specific areas, namely the rivers of the Chui region and the groundwater of the Osh region, are at the highest risk for severe contamination. The spread of pollutants in these areas is primarily driven by the leaching of ferruginous and titanium-containing minerals, as well as industrial chemical residues, which require targeted, site-specific measures to protect water resources. The results also pointed to the need to improve the training of specialists and increase environmental literacy among the heads of mining enterprises and local authorities, enabling them to implement concrete, region-specific environmental roadmaps rather than generalized management strategies.

This will help to effectively cope with the growing environmental challenges and increase the sustainability of ecosystems in mining areas.

For further research in this area, it is necessary to continue exploring methods of ecosystem restoration, such as geoenvironmental solutions and bioremediation, in addition to the introduction of wastewater treatment and pollution reduction technologies for rivers and lakes. It is also essential to continue work on the development of effective monitoring systems to assess the impact of mining enterprises on the environmental situation.

The limitation of the study was the lack of systematic monitoring of ecosystems and insufficient development of long-term forecasts of environmental risks, which limited the accuracy of assessing the impact of mining activities. In the future, it is advised to continue research aimed at drafting highly specific legislative and regulatory measures in the field of environmental protection, such as strict flotation waste regulations for phosphate operations, and the introduction of mandatory innovative technologies, like closed-loop water systems, to definitively minimize local environmental impacts.

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GEOECOLOGICAL PROBLEMS IN THE DEVELOPMENT OF NON-METALLIC DEPOSITS IN KYRGYZSTAN

Keywords

fertilizers, phosphorites, siliceous rocks, magnesite, dolomite

Abstract

The purpose of the study is to examine the geoecological consequences of the development of non-metallic deposits in Kyrgyzstan, with an emphasis on the impact of mining activities on the environment and sustainable development of the region. The work analyses the main environmental

risks associated with open-pit mining, including land degradation, pollution of water bodies, and deterioration of air quality. Particular attention is paid to the impact of mining of building materials such as clay rocks and quartz sands on ecosystems and water resources, especially in areas with intensive mining, where a large number of mining enterprises are concentrated. The study shows that pollution of water resources with chemicals and heavy metals during the processing of minerals requires the introduction of effective purification systems, quality control of reservoirs, and the development of environmentally friendly technologies. Modelling the spread of pollutants in waters allowed identifying the main factors influencing the degree of pollution in different geographical areas and identifying regions with the greatest risk to ecosystems. It is proven that the use of bioremediation and agronomic remediation methods is an effective tool for restoring ecosystems disrupted by mining activities. The study also explores the prospects for the introduction of innovative technologies aimed at reducing environmental impacts, improving the efficiency of mining processes, and minimizing environmental pollution. The results obtained underline the need for an integrated approach to solving environmental problems and the importance of improving environmental monitoring, control systems, and land rehabilitation after the completion of mining. The conclusion underlines the need to improve the skills of environmentalists and specialists in the field of environmental management and the development and implementation of more effective environmental laws and methods of monitoring the activities of mining enterprises to ensure long-term environmental safety and the development of the region.

PROBLEMY GEOEKOLOGICZNE W ROZWOJU ZŁÓŻ NIEMETALICZNYCH W KIRGISTANIE

Słowa kluczowe

nawozy, fosforyty, skały krzemionkowe, magnezyt, dolomit

Streszczenie

Celem badania jest zbadanie geologicznych konsekwencji rozwoju złóż niemetalicznych w Kirgistanie, ze szczególnym uwzględnieniem wpływu działalności górniczej na środowisko i zrównoważony rozwój regionu. W pracy przeanalizowano główne zagrożenia środowiskowe związane z górnictwem odkrywkowym, w tym degradację gleby, zanieczyszczenie zbiorników wodnych i pogorszenie jakości powietrza. Szczególną uwagę zwrócono na wpływ wydobycia materiałów budowlanych, takich jak skały ilaste i piaski kwarcowe, na ekosystemy i zasoby wodne, zwłaszcza na obszarach o intensywnym wydobyciu, gdzie skoncentrowana jest duża liczba przedsiębiorstw górniczych. Badanie pokazuje, że zanieczyszczenie zasobów wodnych chemikaliami i metalami ciężkimi podczas przetwarzania minerałów wymaga wprowadzenia efektywnych systemów oczyszczania, kontroli jakości złóż oraz rozwoju technologii przyjaznych dla środowiska. Modelowanie rozprzestrzeniania się zanieczyszczeń w wodach pozwoliło na identyfikację głównych czynników wpływających na stopień zanieczyszczenia w różnych obszarach geograficznych oraz na identyfikację regionów o największym ryzyku dla ekosystemów. Udowodniono, że stosowanie metod bioremediacji i remediacji agrotechnicznej jest skutecznym narzędziem przywracania ekosystemów zdegradowanych przez działalność górniczą. W badaniu przeanalizowano również perspektywy wprowadzenia

innowacyjnych technologii mających na celu ograniczenie wpływu na środowisko, poprawę efektywności procesów wydobywczych i minimalizację zanieczyszczeń środowiska. Uzyskane wyniki podkreślają potrzebę zintegrowanego podejścia do rozwiązywania problemów środowiskowych oraz znaczenie doskonalenia monitoringu środowiska, systemów kontroli i rekultywacji gruntów po zakończeniu działalności górniczej. Wnioski podkreślają potrzebę doskonalenia umiejętności ekologów i specjalistów w dziedzinie zarządzania środowiskiem oraz opracowywania i wdrażania skuteczniejszych przepisów ochrony środowiska i metod monitorowania działalności przedsiębiorstw górniczych w celu zapewnienia długoterminowego bezpieczeństwa środowiskowego i rozwoju regionu.