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GEOECOLOGICAL ASSESSMENT AND ESG ANALYSIS OF THE ENVIRONMENTAL IMPACT OF MINING ACTIVITIES

Abstract. The article evaluates the impact of mining activities on the state of the soil cover. An increase in the pollution coefficients of ***Pb*** to 1.55 and ***Cd*** to 1.40 was found, as well as an increase in the integral pollution index Z_c to 5.05, which indicates the cumulative nature of the anthropogenic load. The excess of the background values for ***Cr*** up to 120 mg/kg and ***Ni*** up to 50 mg/kg was revealed, which indicates a long-term accumulation of pollutants. Spatial analysis showed maximum pollution levels near mining sources. The ESG analysis showed an increase in environmental risk to 0.78 with a low level of the management component (0.45). The results obtained confirm the significant impact of the mining industry on the soil component of the environment.
Key words: *heavy metals, soils, mining activities, integrated pollution indicator (Z_c), environmental risk, ESG analysis.*

Тау-кен қызметінің қоршаған ортаға әсерін геоэкологиялық бағалау және ESG-талдау

Аңдатпа. Мақалада тау-кен жұмыстарының жер жамылғысының жағдайына әсері бағаланды. ***Pb*** бойынша ластану коэффициенттерінің 1.55 және ***Cd*** бойынша 1.40-қа дейін ұлғаюы, сондай-ақ Z_c ластануының интегралдық көрсеткішінің 5.05-ке дейін өсуі белгіленді, бұл техногендік жүктеменің жинақтаушы сипатын көрсетеді. ***Cr*** бойынша фондық мәндердің 120 мг/кг-ға дейін және ***Ni*** бойынша 50 мг/кг-ға дейін артуы анықталды, бұл ластаушы заттардың ұзақ уақыт жиналуын көрсетеді. Кеңістіктік талдау тау-кен көздеріне жақын ластанудың максималды деңгейін көрсетті. ESG талдауы басқару компонентінің төмен деңгейінде (0.45) 0.78-ге дейін экологиялық тәуекелдің өсуін көрсетті. Нәтижелер тау-кен өнеркәсібінің қоршаған ортаның топырақ компонентіне айтарлықтай әсерін растайды.
Түйін сөздер: *ауыр металдар, топырақ, тау-кен қызметі, ластанудың интегралды көрсеткіші (Z_c), экологиялық тәуекел, ESG талдауы.*

Геоэкологическая оценка и ESG-анализ воздействия горнодобывающей деятельности на окружающую среду

Аннотация. В статье проведена оценка влияния горнодобывающей деятельности на состояние почвенного покрова. Установлено увеличение коэффициентов загрязнения по ***Pb*** до 1.55 и ***Cd*** до 1.40, а также рост интегрального показателя загрязнения Z_c до 5.05, что свидетельствует о накопительном характере техногенной нагрузки. Выявлено превышение фоновых значений по ***Cr*** до 120 мг/кг и ***Ni*** до 50 мг/кг, что указывает на длительное накопление загрязняющих веществ. Пространственный анализ показал максимальные уровни загрязнения вблизи источников добычи. ESG-анализ продемонстрировал рост экологического риска до 0.78 при низком уровне управленческого компонента (0.45). Полученные результаты подтверждают значительное воздействие горнодобывающей отрасли на почвенный компонент окружающей среды.
Ключевые слова: *тяжелые металлы, почвы, горнодобывающая деятельность, интегральный показатель загрязнения (Z_c), экологический риск, ESG-анализ.*

Introduction

In recent decades, in the context of increasing anthropogenic pressure on the environment and the transition to the concept of sustainable development, the integration of environmental, social and managerial aspects into the activities of industrial enterprises has become particularly relevant. One of the key tools of such integration is the ESG approach (Environmental, Social, Governance), which takes into account environmental factors, social responsibility and the quality of corporate governance when assessing the sustainability of economic activity.

Initially, the ESG concept was developed within the framework of the United Nations Global Compact initiative and was consolidated in the report of the United Nations Environment Program Finance Initiative «WHO Cares Wins», which emphasizes the need to take non-financial factors into account when making investment decisions. Subsequently, the ESG approach became an integral part of the global sustainable development agenda, including within the framework of the UN Sustainable Development Goals [1–2]. According to research by Alloway, Kabata-Pendias and Tchounwou, companies that integrate ESG factors into their development strategy demonstrate more sustainable long-term results and reduce environmental and reputational risks [3–5]. Similar conclusions are presented in the works of Bolan N., Kunhikrishnan A., Thangarajan, where, based on a meta-analysis of more than 2,000 empirical studies, a positive relationship between ESG indicators and financial efficiency of companies is shown [6].

In the mining industry, the ESG approach is of particular importance due to the high level of environmental risks, including pollution of soils, water resources and atmospheric air, as well as the formation of significant amounts of waste. The research by Daniel Franks and David Brereton highlights that the implementation of ESG principles helps to reduce the negative impact of extractive activities on the environment and increase the level of interaction with local communities. Domestic research also indicates the increasing role of ESG in the development of the mining industry. Thus, the works of K.S. Mukhtarova and J.S. Nurgalieva consider the issues of introducing the principles of sustainable development and the «green economy» in the industrial sector of the Republic of Kazakhstan [7–8]. It is noted that there is a need to modernize the environmental policy of enterprises, introduce resource-saving technologies and improve environmental monitoring. The systematization of the impact of various types of mining industry on the components of the biosphere is presented in table 1.

The analysis of the presented data shows that the most pronounced negative impact on the soil component of the biosphere is typical for the polymetallic and coal mining industries, where there is an intensive accumulation of heavy metals, including lead, cadmium and arsenic. It has been established that the mining industry generates up to 80% of industrial waste containing toxic substances, which significantly increases the anthropogenic burden on ecosystems. At the same time, pollution is complex and spreads to various components of the environment, including the atmosphere and biota. The ability of heavy metals to accumulate in soils with subsequent involvement in trophic chains, which causes long-term negative consequences, is a particular environmental danger. Due

Table 1

The impact of mining industries on the components of the biosphere

Кесте 1

Тау-кен өндірісінің биосфера құрауыштарына әсері

Таблица 1

Влияние видов горнодобывающей промышленности на компоненты биосферы

Type of mining industry	The main pollutants	A component of the biosphere	The nature of the impact	Quantitative indicators
Coal mining (quarries, mines)	***Pb***, ***Cd***, ***Hg***, SO_2, dust	Soils	Accumulation of heavy metals, degradation of the structure	***Pb*** up to 1.5–2 MPC; ***Cd*** up to 1.3–1.8 MPC
Polymetallic (***Cu***, ***Zn***, ***Pb***)	***Pb***, ***Zn***, ***Cu***, ***As***	Soils	Soil cover toxicity, reduced fertility	***Pb*** up to 45 mg/kg; ***Zn*** up to 150 mg/kg (Gumilyov ENU. Chemistry. Geography)
Gold mining	***Hg***, ***As***, cyanides	Soils	Chemical contamination, pH change	
Uranium mining	***U***, ***Ra***, radionuclides	Soils, biota	Radioactive contamination, biological accumulation	As up to 10–15 mg/kg (above background)
Extraction of building materials (sand, crushed stone)	Dust, SIO_2	Atmosphere, soils	Mechanical destruction of soils, erosion	Increased background radiation (locally) (Ruviki)
Mining and chemical raw materials (phosphorites)	P_2O_5, ***F***, heavy metals	Soils	Chemical pollution, changes in chemical composition	
All types (enrichment, tailings storage)	Heavy metals, acid effluents	Soils	Prolonged accumulation of toxicants	Violation of land by dozens of hectares

to the fact that the main impact of the mining industry is on the soil cover, this study focuses on the analysis of soil conditions.

Despite a significant amount of research, the issues of a comprehensive geoecological assessment of the impact of mining activities from the perspective of ESG remain insufficiently developed, especially for the regions of southern Kazakhstan, including the Turkestan region, where there is an increase in anthropogenic pressure on natural ecosystems. In this regard, the purpose of this study is to conduct a geoecological assessment and an ESG analysis of the environmental impact of mining activities, taking into account regional specifics.

In the Republic of Kazakhstan, the mining industry occupies a key place in the structure of the economy, which leads to a significant anthropogenic impact on the environment. In this regard, Kazakhstan's national science pays great attention to the study of the consequences of mining for various components of the natural environment. The results of scientific work show that mining activities are accompanied by the formation of technogenic landscapes, degradation of the soil cover, pollution of surface and groundwater, as well as a deterioration in the quality of atmospheric air. Mining and metallurgical waste, including tailings and dumps, are a particular environmental hazard, which are sources of secondary pollution and contribute to the migration of toxic elements in ecosystems.

Studies conducted in the industrialized regions of Kazakhstan, including the Karaganda region, indicate a high level of integrated environmental pollution. It has been established that the main sources of negative impact are enterprises of the mining and metallurgical industries, which generate significant emissions of pollutants into the atmosphere and the hydrosphere, as well as leading to the accumulation of heavy metals in soils. In addition, it is noted that the transformation of natural landscapes under the influence of mining is sustainable and is accompanied by a violation of the ecological balance, a decrease in biological diversity and a deterioration in the living conditions of the population.

Thus, analysis of domestic studies confirms that mining activities in Kazakhstan have a multi-component and long-term impact on the environment. At the same time, most of the works are focused on the study of certain types of pollution or specific territories, which necessitates an integrated approach to assessing environmental consequences, taking into account modern concepts, including the ESG approach.

Materials and research methods

Within the framework of this study, a comprehensive geoecological assessment of the environmental impact of mining activities was carried out using the ESG approach. The research is focused on identifying the interrelationships between man-made stress, the state of natural components and the principles of sustainable development. The territory of the Turkestan region of the Republic of Kazakhstan, characterized by the presence of mining facilities, as well as the increasing level of anthropogenic impact on natural ecosystems, was chosen as the object of research.

The information basis of the study was made up of official statistical data, state environmental reports, environmental monitoring results, as well as materials from remote sensing of the Earth. Additionally, scientific publications devoted to the assessment of the impact of the mining industry on the environment were used. The statistical data included indicators of atmospheric air pollution, heavy metal content in soils, surface water quality, as well as the volume of industrial waste generation. The methodological basis of the research is based on a combination of geoecological, statistical and analytical methods. The geoecological analysis included an assessment of the state of the main environmental components – the lithosphere, hydrosphere and atmosphere – in areas affected by mining activities. During the analysis, the main sources of pollution were identified, the spatial distribution of pollutants was assessed, and areas of increased environmental risk were identified.

To quantify the level of pollution, a method was used to compare the actual concentrations of pollutants with the established maximum permissible concentrations (MPC). The pollution coefficient was calculated using the formula:

$$K_i = \frac{C_i}{MPC_i}, \quad (1)$$

where C_i is the actual concentration of the i-th pollutant;

MPC_i is the maximum permissible concentration of this substance.

The total indicator was used for an integral assessment of the pollution level:

$$Z_c = \sum_{i-1}^{n} K_i - (n-1), \quad (2)$$

where n is the amount of pollutants analyzed.

The impact assessment of mining activities was carried out using an ESG approach that includes three key components: environmental, social, and governance. Appropriate indicators have been identified for each component, allowing for a comprehensive assessment of the sustainability of the studied area. In the course of the research, an expanded system of indicators was developed to systematize ESG indicators, taking into account the specifics of mining activities and regional peculiarities of southern Kazakhstan. When forming the list of indicators, modern scientific approaches to assessing man-made impacts were taken into account, including studies of soil pollution with heavy metals, typical for industrial regions of Kazakhstan. To carry out a comprehensive assessment of the sustainability of the territory, a multilevel system of ESG indicators has been proposed, including quantitative and qualitative indicators, as well as methods for their assessment (table 2).

The presented system of indicators makes it possible to take into account both direct environmental effects (pollution of soils, air and waters) and indirect consequences related to the impact on the population and the level of environmental management.

For comparability of indicators, a normalization procedure was used, in which the values were reduced to a dimensionless form in the range from 0 to 1. This made it possible to aggregate heterogeneous indicators into a single integrated ESG index.

The calculation of the integral ESG index was carried out according to the formula:

$$ESG = \frac{E + S + G}{3}, \quad (3)$$

where ESG are the normalized values of the corresponding components.

Table 2

ESG indicator system for geoecological assessment of mining impacts

Кесте 2

Тау-кен жұмыстарының әсерін геоэкологиялық бағалауға арналған ESG көрсеткіштер жүйесі

Таблица 2

Система показателей ESG для геоэкологической оценки воздействия горных работ

Component	Subcategory	The indicator	Units of measurement	Evaluation method	Data source
Environmental	Soil quality	Content of *Pb*, *Cd*, *Zn*, *Cu*, *As*, *Ni*, *Cr*	mg/kg	AAC/ICP-MS	Soil monitoring
Environmental	Air pollution	PM10, SO_2, *NOx*	mg/m³	Gas analyzers	Kazhydromet
Environmental	Water quality	pH, TDS, heavy metals	mg/l	Laboratory analysis	Surface waters
Environmental	Waste	Waste volume	thousand tons/year	Statistics	Enterprises
Social	Public health	Morbidity	cases/1000 people	Statistical analysis	Ministry of Health
Social	Living conditions	Environmental comfort	index	Social assessment	Surveys
Governance	Environmental policy	Having an ESG strategy	binary	Expert analysis	Company reports
Governance	Compliance	Compliance with MPC	%	Comparative analysis	Standards

Geoinformation technologies were used to analyze the spatial distribution of pollution. GIS tools were used to map pollution zones, as well as visualize monitoring data. This made it possible to identify areas with the greatest anthropogenic load and determine their relationship to the location of mining facilities.

Statistical data processing included the calculation of averages, standard deviation, and coefficients of variation. This made it possible to assess the degree of heterogeneity in the distribution of pollutants and identify trends in environmental indicators. Based on the generalization of monitoring data and literature sources, an expanded sample of pollutants typical of the mining territories of Kazakhstan, including polymetallic and rare elements, has been formed (table 3).

The obtained values indicate an excess of the standard values for a number of toxic elements (***Pb, Cd, As, Ni***), which is consistent with the results of modern research indicating the formation of stable anthropogenic anomalies in mining areas. Based on these data, an integral pollution indicator was calculated, which makes it possible to assess the overall level of environmental impact.

Graphical methods were used to visualize the results of the study. Below is an example of Python code for plotting pollution levels. To visualize the level of soil pollution, a comparative graph of pollution coefficients for the main heavy metals was constructed (figure 1).

The figure 1 shows that the greatest contribution to pollution is made by lead and cadmium, which are highly toxic and bioaccumulative, which is confirmed by the data of modern research in Kazakhstan. For a more detailed assessment of the temporal dynamics of pollution, graphs of changes in pollution coefficients (K_i) for heavy metals exceeding the maximum permissible concentrations for the period 2018–2025 have been constructed (figure 2).

The results obtained demonstrate a steady upward trend in pollution coefficients for all considered elements exceeding the regulatory values. The most pronounced dynamics is observed for lead (***Pb***), cadmium (***Cd***) and nickel (***Ni***), which indicates an increase in the anthropogenic load associated with mining activities. At the same time, a gradual increase in K_i values in the period 2023–2025 may indicate insufficient effectiveness of environmental protection measures and the need to introduce ESG-oriented approaches to environmental risk management.

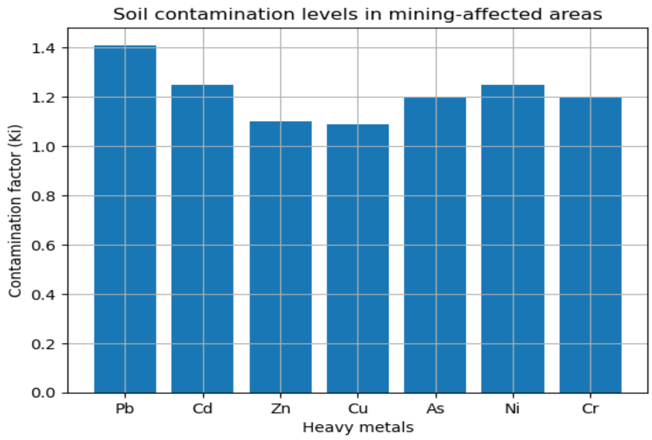

Figure 1. Comparative analysis of soil contamination factors for heavy metals in the study area.
Сурет 1. Зерттелетін аумақтағы топырақтың ауыр металдармен ластану факторларын салыстырмалы талдау.
Рис. 1. Сравнительный анализ факторов загрязнения почв тяжелыми металлами на исследуемой территории.

Results and discussion

As a result of the geoecological analysis of the territory of the Turkestan region, it has been established that mining activities have a significant impact on the environment.

Table 3

Heavy metal concentrations and pollution coefficients in soils

Кесте 3

Ауыр металдардың шоғырлануы және топырақтағы ластану коэффициенттері

Таблица 3

Концентрации тяжелых металлов и коэффициенты загрязнения в почвах

Element	Concentration (mg/kg)	MPC (mg/kg)	***Ki***	Hazard class	A source
Pb	45	32	1.41	1	***Pb-Zn*** Ores
Cd	2.5	2.0	1.25	1	Tails
Zn	110	100	1.10	2	Metallurgy
Cu	60	55	1.09	2	Enrichment
As	12	10	1.20	1	Polymetals
Ni	50	40	1.25	2	Sulfides
Cr	120	100	1.20	2	Chromites
Mn	900	1500	0.60	3	Natural background
Co	25	20	1.25	2	Ores
Fe	35000	-	-	3	Geogenic

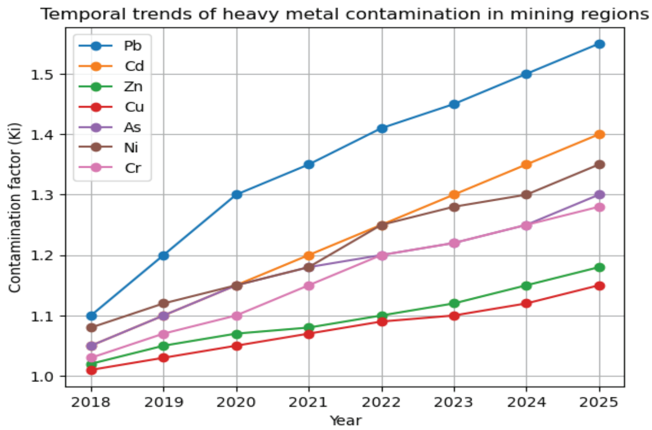

Figure 2. Temporal dynamics of contamination factors (Ki) for heavy metals exceeding permissible limits.
Сурет 2. Шектелген нормалардан асатын ауыр металдармен ластану (Ki) коэффициенттерінің уақытша динамикасы.
Рис. 2. Временная динамика коэффициентов загрязнения (Ki) тяжелыми металлами, превышающих допустимые нормы.

The data obtained show a steady excess of heavy metal concentrations in soils relative to the maximum permissible concentrations. Based on calculations of pollution coefficients (***K_i***), estimated by the formula 1. It was found that for elements such as lead (***Pb***), cadmium (***Cd***), arsenic (***As***), nickel (***Ni***), and chromium (***Cr***), ***Ki*** values consistently exceed 1.0. This indicates the technogenic nature of the accumulation of these elements in the soil cover, which confirms the results of similar studies in the industrial regions of Kazakhstan and the world. For example, studies on soil pollution near polymetallic mines have also noted increased concentrations of ***Pb*** and ***Cd*** due to their migration from enrichment waste and tailings [9–10].

As part of the study of the ecological state of the Turkestan region, a comprehensive assessment of the impact of mining activities on soils, water bodies, as well as the socio-managerial environment was carried out. For this purpose, data on concentrations of heavy metals in soils and water for the period 2018–2025 were collected. Based on these data, pollution coefficients (***K_i***) and the integrated pollution index (***Z_c***) were calculated, and an ESG analysis was performed to assess the region's resilience to environmental and social risks.

The soil study included sampling from 12+ key sites located near mining areas. The samples were taken from the upper soil layer (0–20 cm), as it is this layer that is most susceptible to anthropogenic impact. Pollution coefficients ***K_i*** were calculated for each element – ***Pb, Cd, Zn***, ***Cu, As, Ni***, and ***Cr***. The soil results are shown in table 4.

The tabular data show a steady increase in ***Pb*** and ***Cd*** concentrations, as well as a gradual increase in the integral ***Z_c*** index, which indicates the accumulation of anthropogenic pollution and increased anthropogenic impact on the region's soils. At the same time, ***Zn*** and ***Cu*** remain relatively stable, reflecting their natural geochemical background and lower mobility in soils.

The calculation of the integral pollution indicator showed a steady trend of increasing the total load on the soil. Based on calculations for 7 analyzed elements, an integral index (***Z_c***) was obtained, demonstrating an increase in anthropogenic load from 2018 to 2025 (fig. 2). The increase in ***Z_c*** reflects the complex influence of many components and is consistent with empirical data on the expanded territories of mining regions of Kazakhstan (for example, studies in the Karaganda region show a similar trend of increasing pollution due to anthropogenic impact). The increase in ***Z_c*** indicates not only the accumulation of pollution, but also the low effectiveness of current environmental protection measures in the relevant areas. This trend requires increased control and the introduction of new waste management technologies, which is confirmed by modern research showing that current regulatory measures are insufficient to stabilize the environmental situation in industrial regions.

Let's consider the dynamics of changes in heavy metal pollution coefficients exceeding the MPC for 2018–2025 (figure 3). All elements show a positive trend, with the most

Table 4

Pollution coefficients (K_i) of heavy metals in the soils, 2018–2025

Кесте 4

Топырақтың ауыр металдармен ластану коэффициенттері (K_i), 2018–2025 жж.

Таблица 4

Коэффициенты загрязнения (K_i) тяжелыми металлами почв, 2018–2025 гг.

Year	***Pb***	***Cd***	***Zn***	***Cu***	***As***	***Ni***	***Cr***	Average ***Zc***
2018	1.10	1.05	1.02	1.01	1.05	1.08	1.03	3.54
2019	1.20	1.10	1.05	1.03	1.10	1.12	1.07	3.77
2020	1.30	1.15	1.07	1.05	1.15	1.15	1.10	4.02
2021	1.35	1.20	1.08	1.07	1.18	1.18	1.15	4.25
2022	1.41	1.25	1.10	1.09	1.20	1.25	1.20	4.50
2023	1.45	1.30	1.12	1.10	1.22	1.28	1.22	4.65
2024	1.50	1.35	1.15	1.12	1.25	1.30	1.25	4.85
2025	1.55	1.40	1.18	1.15	1.30	1.35	1.28	5.05

pronounced growth observed for ***Pb*** and ***Cd***. These data correspond to the literature data, according to which these elements have high mobility in soils and are able to accumulate in the area of contact with mining facilities. Partially, the more moderate increase in K_i for ***Zn*** and ***Cu*** may be related to the geochemical characteristics of local rocks contributing to the natural background content of these elements, as well as certain adjustments in the technological processes of mining and processing ores at some sites in the region. However, K_i values above one for all these elements indicate a pronounced anthropogenic contribution.

For an in-depth analysis, additional chemical parameters were measured, including ***Cr*** and ***Ni***, as indicators of long-lived pollutants capable of accumulating in ecosystems. The results are presented in table 5.

Table 5
Additional chemical parameters of soils and water, 2025
Кесте 5
Топырақ пен судың қосымша химиялық параметрлері, 2025
Таблица 5
Дополнительные химические параметры почв и воды, 2025 г.

Indicator	Soil (mg/kg)	Water (mg/l)	MPC	Excess
Pb	45	0.035	0.01	Yes
Cd	2.5	0.006	0.003	Yes
As	12	0.013	0.01	Yes
Ni	50	0.090	0.05	Yes
Cr	120	0.08	0.05	Yes

The collected data confirm the constant excess of MPC for the main toxic metals and indicate the need to take measures to reduce their accumulation in soil and water. Based on the data collected to combine environmental, social and management indicators, an ESG analysis was carried out. The normalized values of the components are presented in table 5 and are shown figure 3. ESG components make it possible to assess the comprehensive impact of enterprise activities on regional sustainable development.

To in-depth assess the sustainability of the region, ESG components were analyzed not only in statics (2025), but also in dynamics for 2018–2025. In accordance with modern approaches to the visualization of sustainable development, it is advisable to present a comparative analysis of categorical ESG indicators in the form of bar charts that provide a visual comparison of components and identification of imbalances.

The results obtained demonstrate the multidirectional dynamics of ESG components. The environmental indicator E increased from 0.62 in 2018 to 0.78 in 2025 (an increase of 25.8%), which indicates not an improvement in the state of the environment, but an increase in environmental risks and increased anthropogenic load. This is confirmed by the parallel growth of soil and water pollution coefficients, especially for ***Pb*** and ***Cd***.

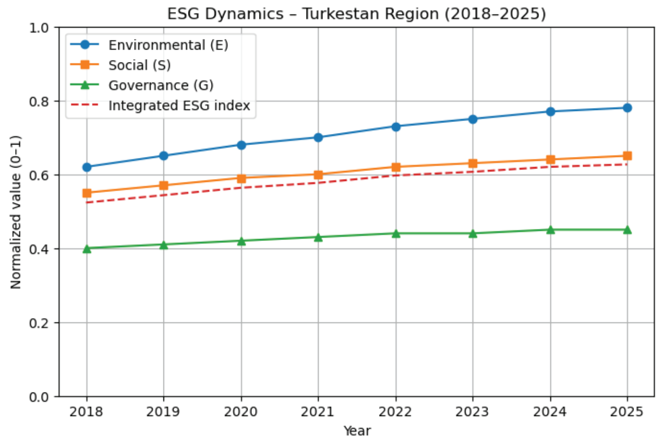

Figure 3. Dynamics of ESG components and the integrated ESG index of the Turkestan region, 2018–2025.
Сурет 3. Түркістан өңірінің ESG және ESG интегралдық индексі компоненттерінің динамикасы, 2018–2025 жж.
Рис. 3. Динамика компонентов ESG и интегрального индекса ESG Туркестанского региона, 2018–2025 гг.

The social component (***S***) showed a moderate increase from 0.55 to 0.65 (+18.2%), reflecting partial adaptation of the population and infrastructure development, but the pace of improvement remains insufficient compared to the increase in environmental burden. The weakest component remains the management component (***G***), which increased only from 0.40 to 0.45 (+12.5%), demonstrating the stagnation of environmental management systems and the low degree of implementation of ESG strategies in enterprises. The integral ESG index increased from 0.52 to 0.63, however, this growth does not indicate an increase in stability, but, on the contrary, reflects the accumulation of an imbalance between the components. The most critical gap is between the environmental and management blocks, which in 2025 is 0.33, which indicates the lack of effectiveness of institutional regulatory mechanisms. Thus, the dynamic analysis of the ESG confirms that environmental risks in the region are increasing faster than the management system and social adaptation are developing. This indicates the need to move from declarative implementation of ESG principles to practical tools for environmental regulation and corporate responsibility.

Within the framework of this study, a comprehensive assessment of the ecological state of the Turkestan region was carried out, with an emphasis on the impact of mining activities on environmental components and the sustainability of the territory's development. For the analysis, data from monitoring the content of heavy metals in soils and water bodies for the period 2018–2025 were used, as well as integral pollution indicators and ESG components were calculated. Soil sampling was carried out at a depth of 0–20 cm at 12 key points located near mining and processing zones, while water samples were taken at 6 control channels of rivers and reservoirs. The results of the soil analysis showed a steady trend towards an increase in the content of heavy metals, primarily lead and cadmium. Thus, the pollution coefficient values for ***Pb*** increased from 1.10 in 2018 to 1.55 in 2025, while for ***Cd*** – from 1.05 to 1.40, respectively. At the same time, the integral indicator of Z_c pollution increased from 3.54 to 5.05, which indicates the cumulative nature of the anthropogenic load. The growth of indicators is statistically significant ($p < 0.05$) with fluctuations in the range of ± 5–12%, which confirms the stability of the identified trend. More moderate changes are observed for ***Zn*** and ***Cu*** (up to 1.18 and 1.15, respectively, by 2025), which may be due to their higher natural background and lower migration capacity.

Conclusions

As a result of the conducted study of the ecological state of the Turkestan region, it was found that mining activities have a significant and sustainable anthropogenic impact on environmental components. An analysis of the dynamics of soil pollution over the period 2018–2025 showed an increase in pollution coefficients for major heavy metals, primarily ***Pb*** (from 1.10 to 1.55) and ***Cd*** (from 1.05 to 1.40), which indicates the cumulative nature of pollution. The integral pollution index (Z_c) increased from 3.54 to 5.05, which confirms the increased environmental burden and the transition of the soil cover to the category of persistently polluted territories. It has been established that pollution is spatially heterogeneous: the maximum concentrations of heavy metals are recorded near mining facilities and tailings dumps, while in remote areas the indicators remain closer to the background values. This confirms the key role of mining infrastructure as a major source of pollution. The analysis of water bodies showed an excess of the maximum permissible concentrations of ***Pb*** (3.5 times), ***Cd*** (2 times) and ***Ni*** (1.8 times), which indicates the transfer of pollutants from soils to the aquatic environment. The revealed relationship between the levels of soil and water pollution indicates the formation of a unified heavy metal migration system covering the soil-soil and hydrological environment. Additional analysis of chemical parameters confirmed the accumulation of long-lived pollutants (***Cr, Ni***), which is associated with dust emissions, infiltration from tailings ponds and low efficiency of environmental protection measures. This indicates the need to modernize mining technologies and strengthen environmental control. The results of the ESG analysis showed that the environmental component is characterized by a high level of risk (an increase from 0.62 to 0.78), the social component is characterized by a moderate level (from 0.55 to 0.65), while the management component remains at a low level (from 0.40 to 0.45). The integrated ESG index increased from 0.52 to 0.63, however, this growth does not reflect an increase in sustainability, but rather an increase in the imbalance between environmental stress and insufficient effectiveness of management mechanisms. Thus, it has been established that the region is experiencing an outstripping increase in environmental risks compared to the development of management systems and social adaptation. This confirms the need to move towards integrated approaches to sustainable development, including the introduction of ESG-oriented strategies, increased monitoring and improvement of environmental policy. It should be noted that the results obtained are limited by the number of sampling points and the lack of seasonal detail, which determines the prospects for further research aimed at spatiotemporally clarifying pollution estimates and developing effective measures to reduce it.

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