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Modern aspects of reclamation of coal mines

K.B. Rysbekov, N.O. Sarybayev*, B. Kakim, Y. Metelev, K. Tileubekov

Satbayev University, Almaty, Kazakhstan

**Corresponding author: n.sarybayev@satbayev.university*

Abstract. The study aims to identify and systematize the main technical, environmental, and biological factors determining the effectiveness of reclamation of lands disturbed by open-pit coal mining. The research was conducted using documentary analysis and a comparative review of domestic and international practices. Technical and biological reclamation projects for the Severnyi and Vostochnyi coal mines in the Ekibastuz coal basin were analyzed together with published data on the restoration of coal-mining areas in the United States, Mongolia, and Indonesia. The comparison covered engineering preparation of the territory, surface runoff management, erosion prevention, soil and vegetation restoration, environmental monitoring, and the economic feasibility of reclamation solutions. It was established that the two technical reclamation options proposed for the Vostochnyi coal mine differ in the scope and total cost of the planned works. The study showed that flattening the slopes of the Festivalnyi, Konveyernyi, and Prybortovoy external dumps is constrained by the risk of spontaneous combustion of carbonaceous rocks, the location of engineering infrastructure, and the possible expansion of disturbed areas into productive land. Comparison with international experience confirmed the need for long-term monitoring of water quality, backfill stability, vegetation development, and soil-forming processes. It was also found that domestic biological reclamation projects mainly rely on natural revegetation, whereas direct planting and fertilizer application may accelerate the formation of a stable vegetation cover. The main constraints and effectiveness factors associated with the reclamation of large coal mines in Kazakhstan were systematized, and directions for adapting international approaches to the conditions of the Ekibastuz coal basin were identified. The results can be used in the development and revision of reclamation projects that incorporate long-term monitoring, surface runoff control, assessment of soil formation, and active vegetation restoration.

Keywords: *coal mining, reclamation, disturbed lands, reclamation phases, monitoring*.

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1. Introduction

Coal has been one of the most used raw materials in the world. The global consumption of coal still remains quite high. Among the leaders are China, India and USA with 5313 million, 1200 million and 476 million tons respectively [1]. Both China and India mostly use the coal for power generation purposes. Our country used about 85 million tons of coal in 2025, which ranks 13th worldwide and mainly for the purposes of electric power generation [1, 2]. However, it should be noted that both China and India saw a drop in the consumption volume for the first time in 52 years [3]. Such a trend could be explained by the shift of both countries towards the cleaner energy sources. Air pollution and climate change are main reasons why countries are turning their attention to cleaner energy sources. Gradual decline in coal demand could mean that operation of coal mines could stop.

At the same time, a reduction in coal production does not eliminate the environmental consequences accumulated during decades of mining. Mine closure creates a need to stabilize disturbed areas, prevent further degradation and return the land to a condition suitable for environmental, agricultural, industrial or recreational use. Therefore, reclamation should be considered not only as a final stage of mine closure, but also as an integral part of the entire life cycle of a mining enterprise [4]. Progressive reclamation, in which disturbed areas are restored while mining operations are still continuing, may reduce the final closure workload and limit long-term environmental risks [5, 6].

Open pit mining of coal has damaging effect on the environment. Those mines usually occupy large areas of land. For example, Ekibastuz coal basin located in the north part of our country has an area of 155 square kilometers. North Antelope Rochelle Coal Mine, located in USA, has a mine permit area of 65805 acres or 266 square kilometers and 3,682 acres of that land were already reclaimed [7]. Reclamation of land at Ekibastuz coal basin has not fully started, because all the mines in the area are fully operational.

The environmental impact of open-pit coal mining is not limited to the direct occupation of land. Mining operations substantially modify the original relief, soil profile, surface runoff and groundwater regime. Waste dumps and exposed slopes may become sources of dust, water erosion, slope instability and contamination of surface and groundwater [8-

10]. Waste dumps and exposed slopes may become sources of dust, water erosion, slope instability and contamination of surface and groundwater. Therefore, assessment of the rock mass condition and management of slope stability should be considered during both mining and reclamation planning [11].

The removal and mixing of soil horizons also reduce soil fertility and complicate the restoration of vegetation. The removal and mixing of soil horizons also reduce soil fertility and complicate the restoration of vegetation, while the migration of contaminants may adversely affect nearby surface-water bodies and underground aquifers [12]. Consequently, successful reclamation requires coordinated geotechnical, hydrological, soil-management and biological measures rather than only surface leveling [13].

The fact that coal is a combustible rock makes the task of reclamation of coal deposits challenging, since special measures should be carried out while reclaiming such deposits [14, 15]. The coal dumps should contain screens with inert materials or non-flammable rocks, compaction level of soil in dumps should be high to avoid seepage of water. All these measures are necessary to prevent oxygen access to coal containing layers of soil [16-19].

The presence of carbonaceous material in overburden and waste dumps creates an additional risk of oxidation and spontaneous combustion. Water infiltration and oxygen penetration may intensify these processes and lead to heat generation, gas emissions and deterioration of dump stability. For this reason, the design of reclamation measures should consider the composition of waste rocks, the distribution of coal-bearing layers, the degree of compaction, drainage conditions and the long-term thermal stability of reclaimed dumps [20, 21].

Reclamation is generally divided into technical and biological phases [22]. The technical phase includes reshaping and stabilization of landforms, backfilling, slope flattening, construction of drainage systems, covering of potentially hazardous materials and preparation of the surface for further use. The biological phase is aimed at restoring soil functions and vegetation through the application of fertile soil, fertilization, seeding, planting or controlled natural succession. The effectiveness of both phases depends on local climatic conditions, soil properties, water availability and the intended post-mining land use [23-25].

Long-term monitoring is also essential because the visible completion of reclamation works does not necessarily mean that the reclaimed ecosystem has reached a stable condition [26]. Vegetation survival, soil development, erosion, surface and groundwater quality, slope stability and signs of residual contamination should be assessed during and after reclamation [27-30]. International practice shows that systematic monitoring supported by GIS, remote sensing and other geospatial technologies makes it possible to identify hazardous changes at an early stage and implement appropriate corrective measures [31].

Domestic reclamation projects already include measures for surface stabilization, drainage, isolation of disturbed areas and subsequent vegetation recovery [32, 33]. However, comparison with international experience indicates that greater attention should be paid to long-term pedogenesis, measurable monitoring criteria, active biological reclamation and the selection of plant species and fertilizers suitable for specific site conditions [34, 35]. These aspects are particularly important for the large coal-mining areas of Kazakhstan, where natural recovery may proceed slowly because of the continental and relatively dry climate.

Therefore, the information given above shows that the problem of reclamation (recultivation) of coal mines is and would be topical.

2. Materials and methods

This study employed a documentary review and comparative case-study approach to identify the main technical, environmental, and biological factors affecting the reclamation of open-pit coal mines. The analysis was based on two groups of information sources: reclamation and mine-closure documentation for coal mines in Kazakhstan, and published studies describing reclamation practices at coal-mining sites in other countries.

The domestic part of the analysis included the Severnyi and Vostochnyi coal mines located within the Ekibastuz coal basin. These sites were selected because they represent large operating open-pit coal mines and have available project documentation describing the planned technical and biological phases of reclamation. The reclamation project for the Severnyi coal mine [32] was examined with respect to landform reconstruction, formation and compaction of the leveling backfill, drainage arrangement, erosion control, use of overburden materials, and the proposed method of vegetation recovery. The mine-closure and reclamation plan for the Vostochnyi coal mine [33] was analyzed to compare alternative technical reclamation options, their estimated costs, monitoring requirements, treatment of external waste dumps, water-management measures, and potential post-mining use of infrastructure.

The international cases were selected to represent reclamation practices related to the principal issues identified in the domestic documentation. The North Antelope Rochelle Coal Mine in the United States was considered as an example of long-term regulatory monitoring and the use of GPS/GIS technologies for assessing reclaimed land [27]. Research on reclaimed coal-mining areas was used to examine the long-term development of soil profiles and pedogenesis [29]. The reclamation of coal-mine waste dumps in Mongolia was considered to assess drainage design and the prevention of water erosion and dump instability [34]. The Indonesian case was included to evaluate the effectiveness of direct planting and fertilizer application during biological reclamation [35].

The information collected was organized according to four groups of assessment criteria:

1). Technical reclamation, including landform reshaping, backfilling, compaction, slope stabilization, isolation of carbonaceous materials, drainage construction, and prevention of spontaneous combustion;

2). Biological reclamation, including soil preparation, natural revegetation, direct planting, selection of plant species, and fertilizer application;

3). Environmental protection and monitoring, including control of soil contamination, dust emissions, wind and water erosion, surface-water and groundwater quality, vegetation development, and residual contamination;

4). Economic and post-mining considerations, including the estimated cost of reclamation alternatives, the possibility of reusing infrastructure, and the intended future use of reclaimed land.

A qualitative comparative analysis was then performed. First, the reclamation measures planned for the Severnyi and Vostochnyi coal mines were compared to identify similarities and differences in technical design, biological restoration, monitoring, and cost. Second, the domestic practices were compared with the selected international cases. Particular attention was paid to measures that were absent, insufficiently developed, or only partly considered in the domestic projects.

The comparison did not aim to rank the examined mines because the sites differ in climatic conditions, mining scale, waste-rock properties, regulatory requirements, and intended post-mining land use. Instead, the analysis was used to identify transferable reclamation principles and practices that could improve the long-term environmental stability of coal-mining areas in Kazakhstan. On this basis, the key factors affecting reclamation effectiveness were identified, including systematic monitoring, long-term soil development, erosion and drainage control, active vegetation establishment, and the allocation of sufficient resources for biological reclamation.

3. Results and discussion

Reclamation of coal-mining areas in Kazakhstan is generally implemented in two successive phases: technical and biological reclamation. Technical reclamation may begin before the complete cessation of mining operations, as the required machinery and infrastructure are still available at the site. Biological reclamation is usually carried out after the completion of the principal earthworks and stabilization of the reclaimed surface. The present study considers the Severnyi and Vostochnyi coal mines of the Ekibastuz coal basin, the largest coal-producing region in Kazakhstan, located in the northern part of the country.

The first case concerns the reclamation plan developed for the Severnyi coal mine. According to the project documentation [32], the disturbed area is proposed to be reclaimed for sanitary and environmental purposes through the construction of a leveling backfill. The proposed measures take into account the sequence and duration of reclamation works, as well as their economic feasibility.

The technical reclamation phase includes the following operations:

– construction of a leveling backfill using overburden materials;
– layer-by-layer placement and compaction of the backfill;
– construction of a protective embankment;
– excavation of a drainage ditch for stormwater diversion;
– subsequent natural revegetation of the reclaimed area.

The reclamation project covers 25.3958 ha of disturbed land. The use of potentially fertile overburden materials is expected to improve the local relief, stabilize the reclaimed surface, and reduce the adverse effects associated with the withdrawal of agricultural land from use. The spatial layout of the reclamation site is shown in Figure 1.

During the technical reclamation stage, it is planned to construct a protective embankment along the upper edge of the leveling fill and to excavate a drainage ditch for the collection and diversion of stormwater from the technological road used to inspect and monitor the condition of the reclaimed area. These measures are intended to prevent uncontrolled surface runoff, reduce water infiltration into the backfill, and maintain the long-term stability of the reconstructed landform.

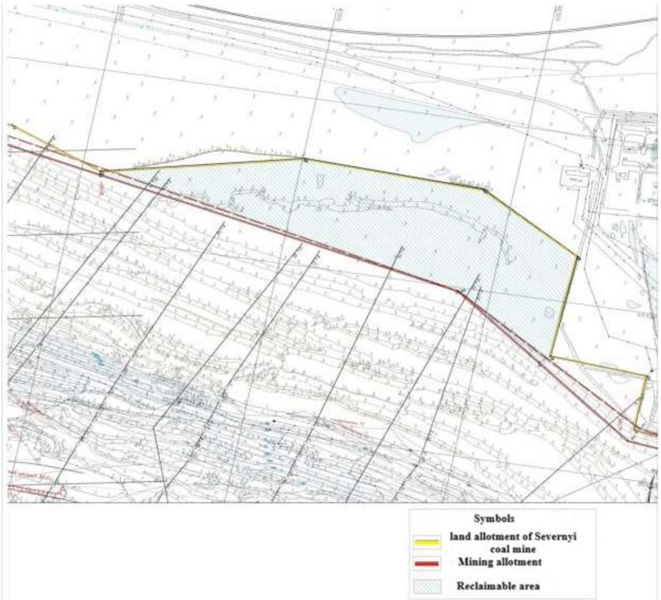

Figure 1. Situational scheme of the reclaimable land in Severnyi coal mine

The technical measures designed to improve the hydrological regime and provide erosion protection for the disturbed territory should include a system of protective and water-diversion embankments delimiting the leveling fill area. The arrangement of these structures is intended to regulate surface runoff, prevent the inflow of water from adjacent areas, and reduce the risk of erosion along the perimeter and slopes of the reclaimed site.

The reclamation project also provides for the construction of interceptor and drainage ditches along the technological road. These structures are required to collect and safely divert stormwater and thereby protect the surface of the leveling fill from water erosion. In combination with surface stabilization measures, they also contribute to reducing wind erosion by limiting the development of eroded and loose surface zones.

Water-diversion and protective structures are constructed from overburden materials using excavators or other earth-moving equipment with equivalent technical capabilities. The use of locally available overburden reduces the need to transport additional construction materials and allows the engineering structures to be integrated into the general configuration of the reclaimed landform. At the same time, the drainage ditch intended to collect and discharge runoff from the technological road is designed with a minimum longitudinal gradient of 5‰, in accordance with the requirements specified in Clause 7.3 of SP 3.03-122-2013. Compliance with this gradient is necessary to maintain the required flow velocity, prevent water stagnation, and ensure the effective operation of the drainage system.

Part of the reclamation site is already occupied by overburden materials previously placed from the pit-side area of the Severnyi coal mine. The existing deposits of overburden are therefore incorporated into the planned configuration of the leveling fill and taken into account when determining the final surface geometry and the required volume of additional material. The estimated volume of overburden materials classified as potentially fertile rocks and required for the formation of the leveling fill within the disturbed land area is 2.197 million m^3, based on the calculated volume of earth materials.

The planned position and spatial configuration of the leveling fill after completion of the reclamation works are shown in Figure 2.

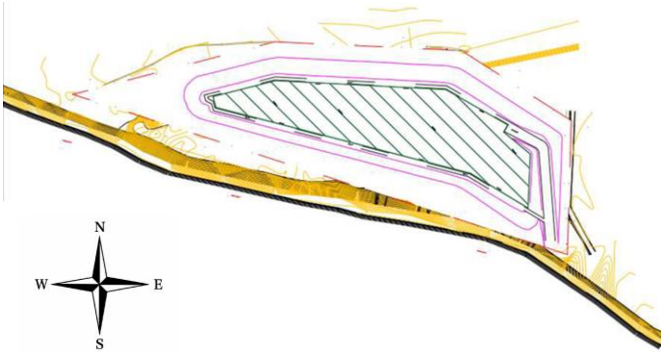

Figure 2. Position of leveling backfill on disturbed lands of Severnyi coal mine

The main part of the biological phase of reclamation in Severnyi coal mine is the natural overgrowth of natural xerophytic vegetation characteristic of this natural and climatic zone based on the soil and climatic conditions of the area and the accepted direction of reclamation.

Overgrowing with perennial grasses will allow:

– stop the process of further pollution of the environment by overburden components;

– improve and streamline the landscape of disturbed lands;

– increase the biological productivity of disturbed lands by increasing the area of green spaces and reducing environmental pollution.

For the period of reclamation, the sources of environmental pollution are parking lots for special equipment and vehicles, where fuel and lubricants may spill, and soil contamination.

When performing reclamation work, the negative impact on the environment is caused by economic activity in the form of emissions of harmful substances into the atmospheric air. The impact of emissions does not exceed the limits of a sanitary protection zone of at least 500 m in size [5].

Overburden rocks meet the radiation safety requirements for building materials and are not radioactive.

Environmental protection measures implemented during reclamation activities at the Severnyi coal mine are aimed at minimizing soil contamination, dust emissions, and erosion processes. Soil pollution is prevented through the organized collection, segregation, and temporary storage of industrial and municipal waste in designated containers, followed by its transfer to authorized disposal or recycling facilities. The adverse effects of wind erosion are reduced by limiting the duration of excavation and earth-moving operations, particularly during periods of dry and windy weather. Dust generation from disturbed surfaces, haul roads, and material handling operations is controlled through the use of water-spraying systems. In addition, engineering measures, including surface grading, soil compaction, drainage channels, and protective embankments, are applied to reduce both wind and water erosion and to ensure the long-term stability of reclaimed landforms.

The second case concerns the reclamation plan developed for the Vostochnyi coal mine in the Ekibastuz coal basin. Vostochnyi is one of the largest open-pit coal mines in the world and is known for the successful implementation of cyclic-and-continuous mining technology. Two alternative options for technical reclamation have been proposed on the basis of the current condition of the disturbed land surface, the natural and climatic characteristics of the area, technical feasibility, economic and socio-economic conditions, and the specific location of the Vostochnyi coal mine [33].

Option 1 includes the following measures:

– clearing the territory of construction waste, coarse-grained materials, and scattered rock accumulations;

– dismantling equipment, buildings, and surface structures designated for removal;

– backfilling ravines, gullies, and erosion channels, as well as leveling local surface irregularities using waste rock;

– constructing a protective embankment around the perimeter of the open-pit mine;

– leaving the reclaimed territory for subsequent natural revegetation;

Option 2 includes the following measures:

– clearing the territory of construction waste, coarse-grained materials, and scattered rock accumulations;

– dismantling equipment, buildings, and surface structures designated for removal;

– backfilling ravines, gullies, and erosion channels and leveling uneven areas using waste rock;

– retaining facilities that remain suitable for further operation during the final stage of mining after the expiration of the current contract or during the development of adjacent and nearby deposits;

– conserving the remaining coal reserves and waste dumps of the Vostochnyi coal mine.

The principal difference between the two alternatives lies in the intended post-mining use of the site and the scope of the reclamation works. Option 1 provides for more extensive isolation and stabilization of the open-pit area, including the construction of a perimeter protective embankment and the subsequent natural revegetation of the disturbed territory. Option 2 places greater emphasis on retaining technically serviceable facilities for possible future use during the development of adjacent or nearby deposits. Consequently, Option 1 requires a larger volume of reclamation works and is more expensive than Option 2, as shown by the comparative cost assessment presented in Table 1.

Table 1. Comparative cost assessment of the technical reclamation options for the Vostochnyi coal mine

Reclamation option	Costs, thousand USD		
	Direct	Indirect	Total
Option 1	34681.30	13211.04	47892.34
Option 2	24565.10	9357.51	33922.61

The biological reclamation criteria established for the Vostochnyi coal mine are intended to ensure that the restored land develops toward a stable target ecosystem. The vegetation established within the reclaimed area should correspond to the composition of the local plant community, and the species used during reclamation should be characteristic of the surrounding natural vegetation. The restored ecosystem should also be capable of retaining water and nutrients, while the physical, chemical, and biological properties of the reconstructed soils should be consistent with those of the target landscape. In addition, the quality of surface water and groundwater affected by acidic or metalliferous drainage should remain within the applicable baseline and regulatory water-quality limits.

The reclamation criteria are formulated in a measurable form so that the condition of the restored area can be objectively compared with reference sites or with land affected by similar mining activities. Their achievement is assessed using quantitative vegetation surveys conducted according to recognized methodological approaches, field measurements, and laboratory analyses of soil samples performed by an accredited laboratory. The evaluation also includes detailed topographic plans and technical specifications of the reconstructed landforms. Particular attention is given to the characteristics of surface drainage, wastewater, and receiving waters, including pH, salinity, and heavy-metal concentrations, which should comply with the established environmental criteria.

Continuous monitoring of the reclaimed area is planned after completion of the biological reclamation works at the Vostochnyi coal mine. The monitoring programme is intended to assess the long-term stability of the reclaimed land, identify signs of residual contamination, evaluate vegetation development, and control the quality of surface water. The proposed monitoring activities, their implementation periods, and recommended frequencies are presented in Table 2.

Table 2. Tentative monitoring schedule for reclaimed areas of the Vostochnyi coal mine

Monitoring activity	Implementation period	Frequency
Inspection of the site for signs of residual contamination	Before and after completion of the reclamation and mine-closure works	Once every six months
Vegetation monitoring to determine the achievement of eradication objectives	After completion of the reclamation and mine-closure works	Once a year
Surface-water sampling for quality control	After completion of the reclamation and mine-closure works	Once a year during the spring flood period
Maintenance and care of established vegetation	After completion of the reclamation and mine-closure works	Once a year

It should also be noted that no rare or endangered food and medicinal plant species subject to special protection have been identified within the area affected by the planned reclamation works at the Vostochnyi coal mine. Therefore, no additional measures specifically aimed at the protection or transplantation of such plant species are required during the biological reclamation phase.

Overburden generated at the Vostochnyi coal mine is stored in three external dumps: Prybortovoy, Konveyernyi, and Festivalnyi. According to the project documentation, the reclamation potential of these dumps is constrained by their structural characteristics, spatial location, and the properties of the stored materials [33].

At the Festivalnyi external dump, internal overburden is removed and placed within the first dump tier. Conventional surface flattening is considered unsuitable because disturbance and redistribution of the stored material may increase oxygen access to carbonaceous rocks and internal overburden, thereby creating conditions for oxidation and spontaneous combustion.

The Konveyernyi external dump is located between other waste dumps and existing engineering infrastructure. Owing to these spatial constraints and the considerable height of its slopes, transferring large volumes of material and flattening the slopes over the surrounding ground surface are considered technically impracticable. Such operations could also interfere with nearby engineering communications and require substantial additional land.

The Prybortovoy external dump is surrounded by undisturbed and biologically productive land. Consequently, flattening its slopes using a top-down approach would extend the dump footprint beyond its current boundaries and result in the additional occupation and disturbance of productive land. This option would therefore contradict the objective of minimizing the total area affected by mining and reclamation activities.

Therefore, flattening the slopes of the external dumps is considered economically unjustified and, in some cases, technically impracticable.

The external dumps are planned to be preserved for further use in accordance with their intended purpose or left for natural revegetation with xerophytic plant species characteristic of the local climatic zone.

The mined-out area is planned to be enclosed by a protective rock embankment with a height of at least 2.5 m, located at a minimum distance of 15.0 m from the edge of the upper bench. The area occupied by each external dump is presented in Table 3.

Table 3. Area occupied by dumps of Vostochnyi coal mine

Title	Area, hectares
Prybortovoy	343.2
Festivalnyi	741.2
Konveyernyi	185.7
Total by all dumps	1270.1

Protective earth embankments were constructed on the upland side of the dumps to prevent flooding by surface runoff. The embankments have a minimum height of 0.6 m, a crest width of at least 0.6 m, and a slope ratio of 1:1.5. Their cross-section is trapezoidal [33]. Buildings and surface structures located at the mine’s industrial site, following the dismantling of technological equipment, as well as roads and engineering communications, may be transferred to local authorities on a contractual basis. These facilities can subsequently be used to support the development of small and medium-sized businesses and to expand the infrastructure of nearby farms.

Reclamation is the responsibility of the subsoil user. However, ensuring that the required reclamation outcomes are achieved is also the responsibility of the relevant state authorities. According to Krzyszowska Waitkus, a GPS/GIS-based system was developed to assist the Wyoming authorities in monitoring reclamation at the North Antelope Rochelle Coal Mine. This approach to sustainable reclamation management contributed to the successful restoration of the mined land within approximately 10 years. The subsoil user submitted annual reports in accordance with Wyoming regulations, after which the responsible state agency verified the reported data, paying particular attention to water quality, backfill condition, and vegetation development [27]. It should also be noted that mining operations at the North Antelope Rochelle Coal Mine have continued, demonstrating that mining and progressive reclamation can be implemented simultaneously when properly organized.

Domestic subsoil users also pay considerable attention to reclamation monitoring, as it is required not only during reclamation works but also after their completion. The example of the Vostochnyi coal mine shows that reclaimed areas should be regularly inspected to confirm that all reclamation measures have been implemented in accordance with applicable national regulations and that the restored land remains environmentally stable.

Full-scale reclamation activities in the Ekibastuz coal basin are not expected to begin in the near future because, according to the Minister of Energy of Kazakhstan, the country's coal reserves could last for approximately 300 years at the current production rate [28]. Nevertheless, the preparation of detailed reclamation and long-term monitoring plans remains an essential requirement of responsible mining.

One aspect of reclamation that is often neglected is soil formation, or pedogenesis. Spasić et al. suggest that attention is generally focused on the upper soil layer, which usually develops during the first 20-40 years after reclamation. However, the lower soil horizons may require up to 100 years to reach a relatively stable condition and may differ considerably from the upper layer. The loss of soil-profile homogeneity results from several interacting factors; according to the authors, particular attention should be paid to the influence of vegetation, especially trees, on the development of reclaimed soils [29]. The disturbance of natural soil homogeneity during mining may adversely affect endemic plant species because there is no guarantee that these species will successfully establish in the newly formed soil profile. Therefore, long-term investigation of soil-forming processes would be useful for domestic mining enterprises. State authorities should also consider pedogenesis as an important component of reclamation assessment and post-reclamation monitoring.

Frauenstein et al. demonstrated that erosion is an important factor that should be considered during the reclamation of coal mines. Their study examined coal-mining areas in Mongolia. According to the authors, a drainage system should be installed around a dump to prevent water erosion and reduce the risk of dump instability. Groundwater inflow into the dump and water accumulation at the toe are two major problems that may arise when the drainage system is inadequately designed. The authors emphasize that the required capacity of the drainage system should be determined by considering the catchment area upslope of the drain, the presence of springs and agricultural drainage systems, and natural surface-water flows that may be affected by the dump [34].

The appropriate design and construction of drainage facilities are also common in domestic reclamation practice. For example, wastewater storage facilities have been created in Lakes Aktygai and Akbidaik to collect water discharged from the Bogatyr and Vostochnyi coal mines [33].

Direct planting combined with fertilizer application may also provide effective biological reclamation results, as demonstrated by Nutayla et al. According to the authors, direct planting of *Pterocarpus indicus* seedlings with the application of bokashi and coal-based fertilizers resulted in a 100% seedling survival rate at a coal mine in Indonesia. The study used bokashi and coal fertilizers and showed that different fertilizer types should be tested and selected according to the specific soil conditions of the reclaimed site. The research was conducted at Pit 3 Barat, IUP Banko Barat, South Sumatra, Indonesia [35].

Unfortunately, active biological reclamation measures are often insufficiently represented in domestic coal-mining practice. For example, the reclamation plans for both the Severnyi and Vostochnyi coal mines, including Option 1 for Vostochnyi, provide for leaving the reclaimed territories to natural revegetation. This approach may be intended to reduce reclamation costs; however, relying exclusively on spontaneous vegetation recovery may prolong ecosystem restoration and may not ensure the establishment of a stable plant community.

4. Conclusions

In an era when decarbonization is a global priority, coal remains an important commodity that cannot yet be completely abandoned, and each country has its own reasons for continuing its use. A significant proportion of coal is extracted by open-pit mining, which occupies large areas of land. Improper reclamation of such territories may lead to serious environmental consequences. Therefore, proper planning, implementation, and long-term monitoring should be key components of any reclamation project. Additional funding for biological reclamation may be necessary and should not be neglected. Reclamation is as important as the mining process itself, since restored lands may subsequently be used for agriculture, industry, infrastructure development, or recreation. International experience shows that systematic monitoring, long-term pedogenesis assessment, effective drainage systems, and direct planting with fertilizer application play an important role in the successful reclamation of coal-mining areas.

It can be concluded that domestic coal-mine reclamation practices are generally promising; however, comparison with international experience indicates that there is still considerable potential for further improvement.

Author contributions

Conceptualization: KBR, NOS; Data curation: BK, KT; Formal analysis: NOS, BK, YM, KT; Formal analysis: BK, YM, KT; Investigation: BK, YM; Methodology: KBR, NOS; Project administration: KBR, NOS; Resources: BK, YM; Supervision: KBR, NOS; Validation: BK, KT; Visualization: YM, KT; Writing – original draft: KBR, NOS; Writing – review & editing: KBR, NOS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Көмір разрездерін рекультивациялаудың қазіргі таңдағы аспектілері

Қ.Б. Рысбеков, Н.О. Сарыбаев*, Б. Кәкім, Е. Метелев, Қ. Тілеубеков

Satbayev University, Алматы, Қазақстан

**Корреспонденция үшін автор:* n.sarybayev@satbayev.university

Аңдатпа. Зерттеудің мақсаты - көмір кен орындарын ашық әдіспен игеру нәтижесінде бұзылған жерлерді рекультивациялау тиімділігін айқындайтын негізгі техникалық, экологиялық және биологиялық факторларды анықтау және жүйелеу. Зерттеу құжаттық талдау және отандық әрі шетелдік тәжірибелерді салыстырмалы қарастыру әдістерін қолдану арқылы орындалды. Екібастұз көмір бассейніндегі «Северный» және «Восточный» көмір разрездерінің техникалық және биологиялық рекультивация жобалары, сондай-ақ АҚШ, Моңғолия және Индонезиядағы көмір өндіру аумақтарын қалпына келтіру бойынша жарияланған деректер талданды. Салыстыру аумақты инженерлік дайындау, жерүсті ағынын реттеу, эрозияның алдын алу, топырақ пен өсімдік жамылғысын қалпына келтіру, экологиялық мониторинг және жобалық шешімдердің экономикалық негізділігі бағыттары бойынша жүргізілді. «Восточный» разрезінің техникалық рекультивациясының екі нұсқасы орындалатын жұмыстар көлемі мен жалпы құны бойынша ерекшеленетіні анықталды. «Фестивальный», «Конвейерный» және «Прибортовой» үйінділерінің еңістерін жайпақтау көмірлі жыныстардың өздігінен жану қаупімен, инженерлік коммуникациялардың орналасуымен және бұзылған өнімді жерлер аумағының ықтимал ұлғаюымен шектелетіні көрсетілді. Шетелдік тәжірибемен салыстыру су сапасын, үйінді жағдайын, өсімдік жамылғысының дамуын және топырақ түзілу процестерін ұзақ мерзімді бақылау қажеттілігін растады. Отандық жобаларда биологиялық рекультивация негізінен табиғи жолмен өсімдік басуын көздейтіні, ал өсімдіктерді тікелей отырғызу және тыңайтқыштарды қолдану тұрақты өсімдік жамылғысының қалыптасуын жеделдете алатыны анықталды. Қазақстанның ірі көмір разрездерін рекультивациялаудың негізгі шектеулері мен нәтижелілік факторлары жүйеленді, сондай-ақ халықаралық тәсілдерді Екібастұз бассейнінің жағдайларына бейімдеу бағыттары айқындалды. Алынған нәтижелер ұзақ мерзімді мониторингті, жерүсті ағынын реттеуді, топырақ түзілуін бақылауды және өсімдіктерді белсенді қалпына келтіруді көздейтін рекультивация жобаларын әзірлеу және түзету кезінде пайдаланылуы мүмкін.

Негізгі сөздер: *көмір өндіру, рекультивация, жердің бұзылуы, рекультивация кезеңдері,мониторинг.*

Современные аспекты рекультивации угольных разрезов

К.Б. Рысбеков, Н.О. Сарыбаев*, Б. Каким, Е. Метелев, К. Тилеубеков

Satbayev University, Алматы, Казахстан

**Автор для корреспонденции:* n.sarybayev@satbayev.university

Аннотация. Целью исследования является выявление и систематизация основных технических, экологических и биологических факторов, определяющих эффективность рекультивации земель, нарушенных открытой разработкой угольных месторождений. Исследование выполнено с использованием документального анализа и сравнительного рассмотрения отечественных и зарубежных практик. Проанализированы проекты технической и биологической рекультивации угольных разрезов «Северный» и «Восточный» Экибастузского угольного бассейна, а также опубликованные данные по восстановлению угледобывающих территорий в США, Монголии и Индонезии. Сравнение проводилось по направлениям инженерной подготовки территории, регулирования поверхностного стока, предотвращения эрозии, восстановления почв и растительности, экологического мониторинга и экономической обоснованности проектных решений. Установлено, что два варианта технической рекультивации разреза «Восточный» различаются объемом работ и общей стоимостью. Показано, что выполаживание откосов отвалов «Фестивальный», «Конвейерный» и «Прибортовой» ограничивается риском самовозгорания углесодержащих пород, расположением инженерных коммуникаций и возможным увеличением площади нарушенных продуктивных земель. Сравнение с зарубежным опытом подтвердило необходимость длительного контроля качества вод, состояния отсыпки, развития растительности и процессов почвообразования. Установлено, что в отечественных проектах биологическая рекультивация преимущественно предусматривает естественное зарастание, тогда как прямая посадка растений и применение удобрений могут ускорить формирование устойчивого растительного покрова. Систематизированы основные ограничения и факторы результативности рекультивации крупных угольных разрезов Казахстана, а также определены направления адаптации международных подходов к условиям Экибастузского бассейна. Полученные результаты могут быть использованы при разработке и корректировании проектов рекультивации, предусматривающих долгосрочный мониторинг, регулирование поверхностного стока, контроль почвообразования и активное восстановление растительности.

Ключевые слова: *добыча угля, рекультивация, нарушенные земли, этапы рекультивации, мониторинг.*

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