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Original Article

# Assessment of the state of vegetation cover of recultivated dumps of uranium deposits in Northern Kazakhstan

## Avaliação do estado da cobertura vegetal de lixões recultivados de depósitos de urânio no norte do Cazaquistão

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**Abstract**

The purpose of this study was to assess the processes of plant community formation on recultivated dumps of spent uranium-containing industrial waste from uranium deposit mines, as well as to identify the degree of impact of agro-climatic factors, agrochemical indicators of soils of recultivated dumps, and the level of residual ionizing radiation on the productivity of the emerging vegetation cover. Studies of plant colonization of recultivated Grachevsky and Shantobinsky uranium mine dumps located in Northern Kazakhstan were carried out. The mining and technical stage of reclamation consisted of planning a dump with slopes of 15° and covering it with a 1 m layer of chestnut soil. In total, 30-35 plant species are present in the dumps, the projective coverage is approximately the same (56.6-70.0%), and the herbage density is 15-16.6 plants/100 m$^2$. As a result of the measures taken to recultivate the dumps, the intensity of the background ionizing radiation at the Grachevsky mine dump was in the range of 25-35 μR/hr and at the Shantobinsky mine dump 10-25 μR/hr, which indicates compliance with safety standards. The plant species which can be used for artificial plant colonization of uranium-containing waste dumps, were identified.

**Keywords:** cenopopulation, environmental monitoring, floristic composition, plant community, population, species projection coverage, uranium mine.

**Resumo**

O objetivo deste estudo foi avaliar os processos de formação de comunidades vegetais em lixões recultivados de resíduos industriais contendo urânio gasto de minas de depósito de urânio, bem como identificar o grau de impacto de fatores agroclimáticos, indicadores agroquímicos de solos de lixões recultivados e o nível de radiação ionizante residual na produtividade da cobertura vegetal emergente. Foram realizados estudos de colonização vegetal de lixões de minas de urânio de Grachevsky e Shantobinsky recultivados localizados no norte do Cazaquistão. A etapa minerária e técnica de recuperação consistiu no planejamento de um lixão com declives de 15° e cobrindo-o com uma camada de 1 m de solo castanheiro. No total, 30-35 espécies de plantas estão presentes nos lixões, a cobertura projetiva é aproximadamente a mesma (56,6-70,0%) e a densidade de forragem é de 15-16, 6 plantas/100 m$^2$. Como resultado das medidas tomadas para recultivar os lixões, a intensidade da radiação ionizante de fundo no lixão da Mina de Grachevsky estava na faixa de 25-35 louboutr/h e no lixão da Mina de Shantobinsky 10-25 scootr/h, o que indica o cumprimento das normas de segurança. Foram identificadas as espécies vegetais que proporcionam a colonização mais dinâmica e formam a sucessão vegetal primária, que pode, portanto, ser utilizada para colonização vegetal artificial de lixões contendo urânio.Palavras-chave: cenopopulação, monitoramento ambiental, composição florística, comunidade vegetal, população, cobertura de projeção de espécies, mina de urânio.

**Palavras-chave:** cenopopulação, monitoramento ambiental, composição florística, comunidade vegetal, população, cobertura de projeção de espécies, mina de urânio.

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## 1. Introduction

The ecology of uranium deposits and the reclamation of the territories of uranium mines are among the priorities in the work of the International Atomic Energy Agency (IAEA) and several other international organizations (Bugubaeva et al., 2023). The importance of conducting a safety assessment and working out mechanisms for the recultivation of industrial dumps composed of spent uranium-containing waste from uranium mines is also certainly an important task. This is reflected in the decisions of international and interstate bodies, including the IAEA and the Commission of the Commonwealth of Independent States on the use of atomic energy for peaceful purposes (IAEA, 2004; Russia, 2023).

Assessment of the ecological state and carrying out work on the reclamation of waste dumps made of spent mining technological waste is an urgent task aimed at ensuring the safety of the environment and the recultivation of lands subjected to catastrophic anthropogenic impacts (IAEA, 2004; Liu et al., 2022; Pandey and Bauddh, 2018). To date, mechanisms for environmental monitoring and recultivation of industrial waste from mining and primary processing of uranium-containing ores, iron and polymetallic ores, coal quarry dumps, and ash dumps of thermal power generating enterprises have been sufficiently studied and tested in practice (IAEA, 2004).

One of the most important indicators of successful reclamation of dumps/tailings of industrial waste from uranium mines, as well as dumps/tailings of other mining and processing industries, is the natural plant colonization and formation of a stable vegetation cover on the surface of such dumps/tailings (Grafkina et al., 2023). The processes of primary succession of vegetation cover on the surface of dumps/tailings of uranium-containing waste and natural plant colonization of recultivated dumps/tailings are certainly environmentally significant issues (Nasiyev et al., 2022a; Mukhanov et al., 2023). The study of the floristic composition, the processes of formation of plant communities in coal and ash dumps, on the dumps of iron ore and polymetallic mines, as well as the influence of plants on the emerging soil layer, is a potential object of detailed scientific study (Bugubaeva et al., 2022; Lin et al., 2017).

The vegetation cover acts as an effective natural protection of the emerging soil cover of dumps/tailings of any type of waste from the effects of erosion, as well as a natural storage of heavy metals (Sarsembayeva et al., 2021) and radionuclides. The root system of plants ensures the consolidation of the soil and acts as a cementing link in the process of soil formation and the emergence of a fertile layer. The appearance of the soil layer and vegetation cover on the dumps/tailings of industrial waste of any type of mining and processing industry is one of the most important conditions for the recultivation of the territories (Abreu et al., 2014; Bugubaeva et al., 2022; Lin et al., 2017).

Many authors emphasize the importance of research in such a relatively new and very effective field of environmental engineering as phytoremediation, which uses plants for the treatment and control of industrial waste in soil, water, and air. The practical goals of phytoremediation also include assessing the processes of absorption of heavy metals and radionuclides by plants, the impact on the formation of the soil composition of reclaimed dumps/tailings, and environmental restoration (Chen et al., 2020; Madejón et al., 2022). Several researchers have conducted detailed studies within the framework of phytoremediation methods to assess the processes of accumulation of radionuclides in plants of recultivated dumps/tailings of uranium-containing waste (Abreu et al., 2014; Chen et al., 2020; Madejón et al., 2022).

The number of publications related to the study of the processes of plant community formation on recultivated uranium-containing waste dumps/tailings from uranium deposit mines is very low. This is explained by the classified research facilities, the very narrow specifics of the conducted research, and the need to ensure the radiation safety of researchers working with potentially dangerous objects.

The study (IAEA, 2004) indicates that the vegetation cover provides good protection against erosion of the applied protective layer that covers dumps and tailings. However, the need for special studies is emphasized to establish which plant ecosystem will be stable under given conditions. One of the recommendations for maintaining vegetation cover is the use of polymer coatings that reinforce the soil layer (IAEA, 2004).

Wen et al. (2004) emphasize that the formation of vegetation cover on the surface of the coating of reclaimed dumps is one of the important measures to achieve long-term stabilization and isolation of uranium production tailings. In Southern China, vegetation plays an active role in preventing the erosion of dumps due to heavy rainfall and in preserving restored tailing dumps following the nature of the surrounding landscape. The same researchers point to the need for the selection of plant species to restore vegetation on the surface of dumps after applying multilayer coatings on them and suggest the following procedure for selecting plant species:

1) focusing on local long-lived herbs;
2) the plants should not require special care or should not require care for a long time;
3) the root system of grasses should be strongly developed to protect against erosion of the soil covering dumps/tailings (Wen et al., 2004).

German scientists Hagen and Jakubick (2011) provide recommendations on the formation of a soil layer on the dumps to colonize the surface of the dumps, which additionally serves as protection against released radionuclides and radon. In (Lin et al., 2017), a group of authors presents the procedure for calculating the vegetation cover coefficient as a key moment for modeling soil erosion, which can also be applied when describing the processes of stability of the soil cover of reclaimed dumps/tailings.

Despite the great importance of uranium mining for the economy of the Republic of Kazakhstan, as well as large areas occupied by uranium deposits in Kazakhstan, including those already preserved, there are virtually no works devoted to the formation of phytocenoses at such facilities in Kazakhstan. In our previous work, we monitored various territories to study phytocenoses and microbial communities of industrial waste dumps of mining enterprises, as well as lands in economic use (Nugmanov et al., 2022a, b; Valiev et al., 2018, 2019).

In 2022, we conducted trial work to study the state of the plant community on the shores of the reservoir of the Grachevsky uranium deposit, previously used as a natural reservoir of effluents from dumps of uranium-containing waste (Bugubaeva et al., 2022).

The purpose of this research is to assess plant community formation, agro-climatic factors, soil properties, ionizing radiation levels, and phytoremediation potential on recultivated dumps containing spent uranium-containing waste from uranium mines.

Considering the practical importance of restoring vegetation cover and the formation of the soil layer of recultivated dumps/tailings of uranium-containing waste, as well as based on the results of a preliminary analysis of scientific material and our previous studies (Bugubaeva et al., 2022; Nugmanov et al., 2022a, b; Valiev et al., 2018, 2019), we set the following goals:

1) assessment of the processes of plant community formation on recultivated spent uranium-containing industrial waste dumps from uranium deposit mines;
2) identification of the degree of influence of agro-climatic factors, agrochemical indicators of soils of reclaimed dumps, and the level of residual ionizing radiation on the productivity of the emerging vegetation cover.

During the study, the following tasks were set and detailed:

1) conducting a floristic assessment of the vegetation cover of dumps;
2) identification of plant species that provide the most dynamic colonization and form the primary plant succession;
3) study of the level of ionizing radiation on the surface of recultivated dumps;
4) study of agro-climatic indicators of regions and their potential impact on the formation of vegetation cover of dumps;
5) study of requirements for agrochemical control of soil composition and properties and development of physicochemical control methods in accredited testing laboratories;
6) conducting studies of soil samples from dumps concerning the main agrochemical quality indicators.

## 2. Materials and Methods

### *2.1. General description of research objects*

Grachevsky uranium mine (location coordinates 53º 18'42" N, 68º 01'18" E, altitude 321 m above sea level) is located in the Ayyrtau district of North Kazakhstan region (Figure 1). The mine is located 3 km north-west of the village of Saumalkol. The Shantobinsky uranium mine (location coordinates 52º 27'22" N, 68º 12'38" E, altitude 390 m above sea level) is located in the Sandyktau district of the Akmola region (Figure 2). The mine facilities are located in the territories adjacent to the village of Shantobe.

Historically, the Grachevsky uranium mine was the largest uranium ore mining enterprise in the North Kazakhstan region and occupied an area of 60.5 ha. Uranium mining has been carried out since 1965. In 1998, the work of the mine was stopped and it was put on maintenance. Now, the main part of the mine facilities has been cultivated. The mine is located northwest of the village of Saumalkol (Figure 2).


**Figure 1.** Location of uranium mines on the map of the Republic of Kazakhstan: (1) Shantobinsky mine; (2) Grachevsky mine.

During the study of objects at the Grachevsky deposit, we selected a recultivated dump of industrial spent uranium-containing waste with an approximate area of 0.04 $km^2$ (Figure 3).

The main works on the mining and technological stage of the reclamation of the dump were carried out in the period from 1999 to 2010. The mining and technical stage of the dump reclamation mainly focused on planning slopes at an angle of 10-15° and applying chestnut soil with a layer of about 1 m. Sowing of perennial grasses was not carried out and the dumps were left to be colonized by random species. The general view of the dump from the southeastern side against the background of the former buildings of the enterprise is shown in Figure 4.

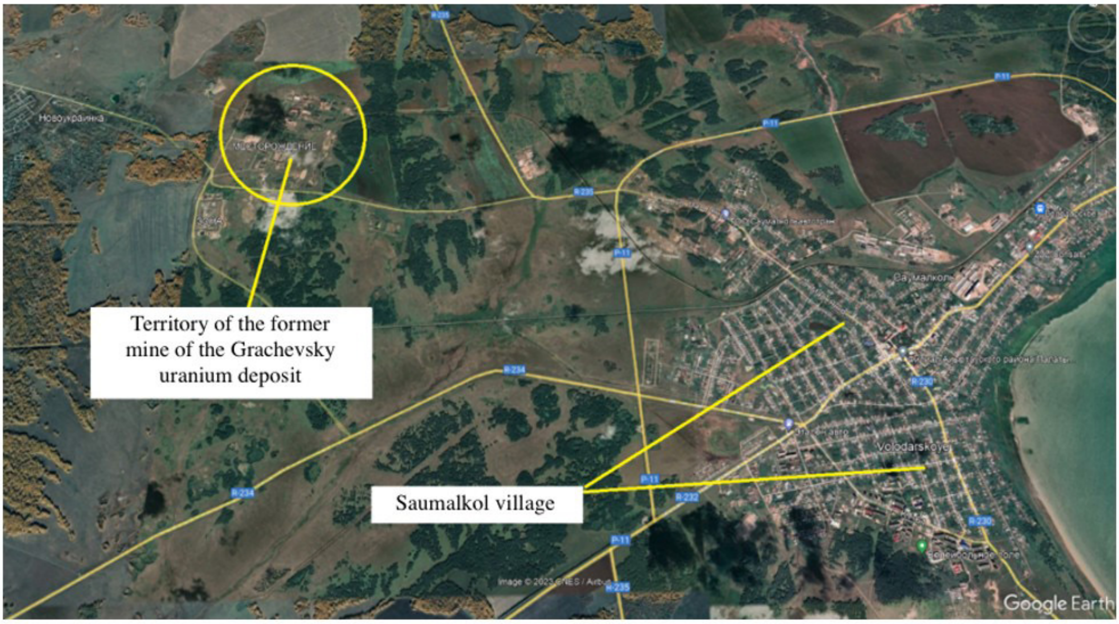


**Figure 2.** Satellite view of the location of the Grachevsky deposit mine.

**Figure 3.** Satellite view of the recultivated dump of the Grachevsky mine. The boundaries of the dump are highlighted in yellow.

The Shantobinsky uranium mine (Shantobe settlement, Akmola region) was founded in 1956 due to the beginning of the development of uranium ore mining from the Bal Kashinskoye deposit. In the period from 2012 to 2014, mining operations at the mine were stopped. The objects on the territory of the mine are currently in the stage of conservation and reclamation. Certain sections of the mine, in particular industrial waste dumps directly adjacent to the village of Shantobe, underwent reclamation in the period from 2001 to 2010. The recultivated mine is located to the north of the village of Shantobe (Figure 5).

During the work on the study of objects at the Shantobinskoye field, a recultivated dump of spent uranium-containing waste with an approximate area of 0.28 km$^2$ was selected as the object of research. The dump is adjacent to the northern part of the village of Shantobe (Figure 5). In the satellite image, the boundaries of the dump are highlighted with a yellow line (Figure 6).

The main works on the mining and technological stage of the reclamation of the dump were carried out in the period from 2001 to 2010. The mining and technical stage of the dump reclamation mainly focused on planning slopes at an angle of 10-15° and applying chestnut soil with a layer of about 1 m. Sowing of perennial grasses was not carried out and the dumps were left under random plant colonization. As of July 2022, the general view of the dump is a hill-shaped formation with an angle of inclination of the sides equaling from 10 to 15°. The general view of the recultivated dump is shown in Figure 7.

**Figure 4.** General view of the recultivated dump of the Grachevsky mine.

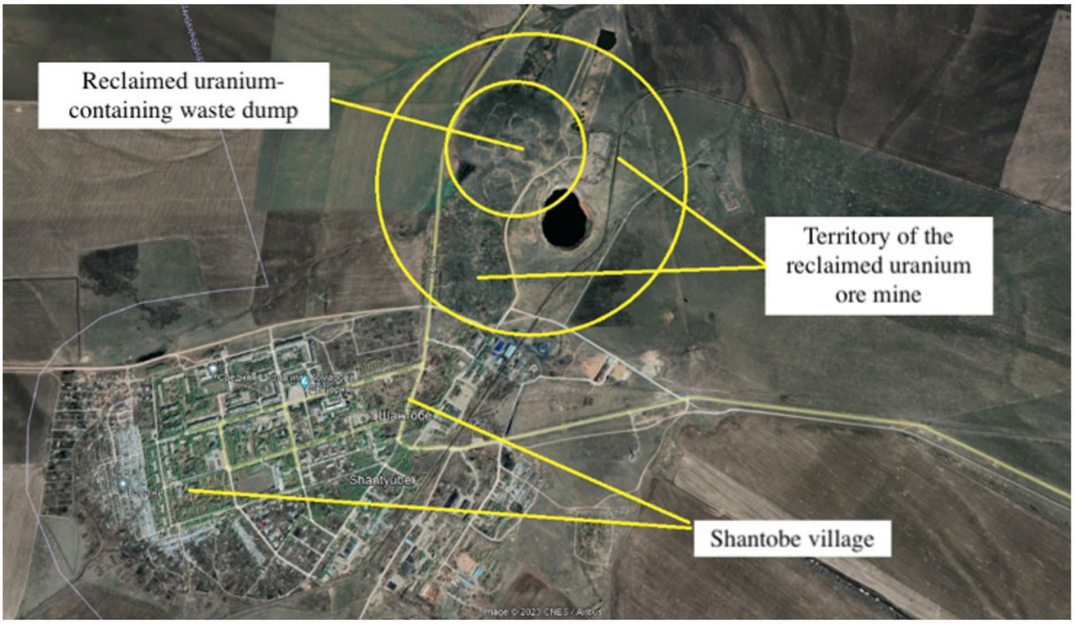


**Figure 5.** Satellite view of the village of Shantobe and the territory of the reclaimed uranium mine.

**Figure 6.** Satellite view of the recultivated dump of uranium-containing mine waste. The boundaries of the dump are highlighted in yellow.

**Figure 7.** General view of the recultivated dump of the Shantobinsky mine.

*2.2. Organization and conduct of the study*

*2.2.1. Investigation of the floristic composition and density of vegetation cover*

When studying the floristic composition and the stage of syngenesis of the vegetation cover, we used classical methods and our developments (Kupriyanov, 2020; Rozenberg, 2018). When organizing the selection of plant material, we also used the rather detailed recommendations of the IAEA (Barnekow et al., 2019).

Qualitative accounting of plants was carried out according to the methods described in Kupriyanov (2020). The number of species (pcs), occurrence, %, and partial projective coverage, % were determined. For the total assessment of the cenotic position of the species, a complex indicator of the activity of the species was used, which shows the measure of the life success of the species in a given territory, one of the expressions of the position of the species in a given flora.

The calculation of species activity was carried out in the IBIS system according to the Formula 1:

$$\text{Act} = \sqrt{\frac{C\times 100\%}{N}\times\frac{\sum_{i=1}^{N}A_i}{N}} = 10\times\frac{\sqrt{C\times A_{\Sigma}}}{N}\% \qquad (1)$$

where *Act* is the estimated activity of the taxon for the monitoring area as a percentage (0-100%); *N* is the number of accounting sites (elementary meter samples); *C* (taxon constancy) is the absolute number of accounting sites where the taxon has been registered; $A_i$ is the projective coverage of a taxon on the i-th accounting platform; $A_{\Sigma}$ is the sum of the projective covers of the taxon on all accounting sites.

For the flora of dumps, the coefficient of synanthropization was calculated according to the formula proposed by Prokopev et al. (2007). The coefficient of synanthropization considers the total occurrence of synanthropic and hemerophobic species.

$$K_s = \sum_{i=1}^{N_a} a_i \times 100 \div \left(\sum_{i=1}^{N_a} a_i + \sum_{i=1}^{N_b} b_i\right)$$

where $K_s$ is the coefficient of synanthropization; $a_i$ is the occurrence of synanthropic species; $N_a$ is the number of synanthropic species; $b_i$ is the occurrence of hemerophobic species; $N_b$ is the number of hemerophobic species.

When assessing the state of vegetation and sampling, the surface of the dumps was conditionally divided into three parts: the base, the middle, and the top of the dump. Accordingly, the study of vegetation cover was carried out at the base of the slope, in the middle of the slope and at the top of the reclaimed dumps. Sampling of plant and soil materials was also carried out at the base, middle part and top.

To account for the aboveground phytomass at each ecotope in 8-fold repetition, cutting was carried out at the soil level. The lab treatment was carried out on the same day. Each fraction was wrapped in paper, dried, and weighed. The fractions were dried in a drying cabinet of the TS-200 SPU type with forced ventilation at a temperature of 50 °C to a constant air-dry state and re-weighed on technical scales of the VLKT-500 type with an accuracy of 0.1 g.

When assessing the species composition, it is possible to identify so-called ruderal species. In our study, we consider those species that do not belong to the steppe, meadow-steppe, meadow plants of Northern Kazakhstan to be conditionally ruderal plants.

*2.2.2. Assessment of the background of ionizing radiation*

Simultaneously with the selection of plant and soil samples, a radiological examination was carried out in the field. Monitoring of the intensity level of ionizing radiation was also necessary to ensure the health and safety of the participants of the working group. The gamma background was measured along the route. The assessment of the level of ionizing radiation on the ground in the field was carried out considering the requirements of regulatory documents and recommendations of researchers. This issue has been sufficiently detailed and described in the current regulatory documents of the Republic of Kazakhstan and scientific recommendations (Gallucci, 2021).

In this work, when measuring the level of ionizing radiation, a dosimeter-radiometer of the MKS-AT6130 type was used (Manufacturer: NP UP ATOMTECH, MNIPI JSC, Republic of Belarus, Minsk), which has type approval of measuring instruments in Russia and Kazakhstan and a valid certificate of state verification of measurement systems.

*2.2.3. Organization and control of agrochemical parameters of soil samples*

The evaluation of agrochemical parameters of soil samples collected from dumps was carried out in an accredited laboratory using certified methods and measuring instruments. One combined sample was taken from each elementary site. Point samples were taken to the depth of the arable layer from 0 to 20 cm, considering the humus horizon. The combined sample on all types of soils was made up of 20 to 25 point samples. The mass of the combined sample was in the range of at least 1.5 kg.

During the control of soil samples, a survey for the content of heavy metals was also carried out. When carrying out physicochemical methods of laboratory control, we used standardized measuring instruments such as pH meter/ionometer Itan (Russia, NPP Tomanalit LLC), photoelectric concentration colorimeter (KFK) 3-01 (Russia, Zagorsky Optical and Mechanical Plant), flame photometer PFA 378 (USA, UNICO), and TDS-meter (Korea, Hanna, Combo), MGA 915 (Russia, Lumex LLC) as the main analytical equipment. The measuring instruments have the necessary approvals for measuring instruments in Russia and Kazakhstan and valid certificates of state measurement system verification.

*2.2.4. Statistical processing of measurement results*

According to the results of statistical processing, the result was displayed in the form of an estimate of the measured value (the arithmetic mean of the corrected measurement results) and the average square deviation of the group containing n measurement results. As the main software tool for statistical processing of measurement results, we used the standard Microsoft Office Excel packages of the 2016 version.

## 3. Results

*3.1. General characteristics of the floristic composition of recultivated dumps*

The vegetation cover was studied at the base of the slope, in the middle of the slope, and at the top of the reclaimed dump (Table 1). The following data were obtained.

Due to the fact that after the reclamation of the dumps, endemic species are repopulated on them, it can be argued that the dumps are a place of secondary habitat. The average density of species in the dumps is 15-16.6 pcs/100 $m^2$.

*3.2. Assessment of the background of ionizing radiation*

When monitoring the intensity level of ionizing radiation of the gamma background of the surface of reclaimed dumps, values were obtained that did not exceed the maximum permissible values established by regulatory requirements (Table 2). During the study of the dumps, it was noted that the intensity of ionizing background radiation at the Grachevsky mine dump was 25-35 μR/hr and at the Shantobinsky dump 10-25 μR/hr, which meets the regulatory requirements for environmental safety. This level of ionizing radiation practically does not affect the formation of phytocenoses.

*3.3. Agrochemical assessment of sample soil composition*

According to the results of monitoring of soil quality and fertility indicators, the following results were obtained (Table 3).

The soils of the dumps have an alkaline reaction (pH more than 6.0). The reaction of the medium affects the ability of plants to absorb nutrients from the soil. At lower pH, it decreases. pH affects the migration and accumulation of substances in the soil, including toxic ones. According to the content of organic substances (humus), the soil samples in question belong to the first group according to the Tyurin method, with the lowest content, below 2%. The nitrogen content in the nitrate form is also very low, less than 30 mg/kg according to the methods (guidelines) of Tyurin and Kononova. The content of mobile phosphorus compounds according to the Machigin method is very low, less than 10 mg/kg.

**Table 1.** General characteristics of the floristic composition of recultivated dumps.

| Descriptions | Coordinates, intensity level of ionizing radiation | Total projective coverage, % | Dominant species | Number of species |
|---|---|---|---|---|
| **1. Grachevsky mine** | | | | |
| Slope base | 53.3120° N, 68.02755° E, 336 m above sea level, 30-35 μR/hr | 60 | *Bromopsis inermis*, *Artemisia absinthium*, *Vicia tenuifolia* | 14 |
| Slope | 53.3120° N, 68.02755° E, 336 m above sea level, 30-35 μR/hr | 70 | *Elytrigia repens*, *Artemisia dracunculus*, *Euphorbia virgata* | 11 |
| Top of the dump | 53.3120° N, 68.02755° E, 336 m above sea level, 25-30 μR/hr | 80 | *Calamagrostis epigeios*, *A. absinthium*, *Cirsium setosum* | 20 |
| **2. Shantobinsky mine** | | | | |
| Slope base | 52.46721° N, 68.18835° E, 393 m above sea level, 15-30 μR/hr | 50 | *A. absinthium*, *B. inermis*, *V. tenuifolia* | 23 |
| Slope | 52.46347°N, 68.1875° E, 400 m above the sea level, 15-25 μR/hr | 50 | *A. absinthium*, *A. austriaca*, *E. repens* | 12 |
| Top of the dump | 52.46913° N, 68.18655° E, 416 m above sea level, 10-20 μR/hr | 70 | *Artemisia proceraeformis*, *E. repens*, *E. virgata* | 15 |

**Table 2.** Values of ionizing radiation intensity indicators, μR/hr.

| No. | Place of control | Grachevsky dump | | | Shantobinsky dump | | |
|---|---|---|---|---|---|---|---|
| | | Number of measurements | Average | Standard deviation | Number of measurements | Average | Standard deviation |
| 1 | Slope base | 30 | 33 | 5.2 | 30 | 26.8 | 4.8 |
| 2 | Middle part | 20 | 29.3 | 4.7 | 20 | 21.2 | 3.8 |
| 3 | Top | 25 | 26.7 | 3.9 | 10 | 15.8 | 1.9 |

The content of mobile potassium compounds according to the Machigin method in the samples of the Grachevsky mine is high (in the range of 401-600 mg/kg), and in the samples of the Shantobinsky deposit is elevated (in the range of 301-400 mg/kg).

In general, such important indicators of potential soil fertility as humus, nitrogen, and phosphorus are relatively low and unfavorable for the formation of highly productive vegetation cover.

To enhance the growth and intensification of the formation of the vegetation cover of dumps, it is necessary to carry out measures to saturate the soils with mobile easily digestible forms of nitrogen and phosphorus compounds in the form of mineral fertilizers.

The standard deviation from the result of the average assessment of the measured values of soil samples in terms of the content of mobile forms of sulfur, phosphorus, and mineral components indicates an uneven chemical composition of the surface indicators of reclaimed dumps. It could be that when applying the coating on recultivated dumps, the imported soil was taken from different sources.

According to the results of monitoring the heavy metal content in the total form in soil samples, the following results were obtained (Table 4).

Zinc belongs to group No. 1 with the lowest content (less than 50 mg/kg). Copper also belongs to group No. 1 with the lowest content (less than 25 mg/kg). The total iron content in soil samples is high enough, and that theoretically provides plants with its soluble mobile forms. The manganese content in the soil is less than 750 mg/kg. Manganese also belongs to group No. 1 with the lowest content.

The content of heavy metals in total form in the studied soil samples generally meets regulatory requirements. The maximum permissible concentration (MPC) for the total content of heavy metals in the soil should have the following values: the MPC of zinc is less than 100 mg/kg, the MPC of copper is less than 50 mg/kg, the MPC of manganese is less than 1,500 mg/kg, the MPC of lead is 30 mg/kg. The total maximum iron content in soil samples of reclaimed dumps is approximately two to three times less than the recommended values, which can reach 38,000 mg/kg (Kupriyanov, 2017). The total form of lead content also corresponds to the hygienic standards for the safety of the habitat of the Republic of Kazakhstan no more than 32 mg/kg. The cadmium content in the soil of the Grachevsky dump is 0.56 mg/kg, which exceeds the MPC standards by about two times. The cadmium content in the soil of the Shantobinsky dump is within the norm.

### *3.4. Assessment of the impact of agro-climatic factors on vegetation cover density and projective cover*

Both mines are located in approximately the same climatic conditions (Table 5). The climate of both areas is continental. Summers are warm and winters are cold. The resources of solar radiation in this region are sufficient for long-day plants and optimal vital activity of crops.

**Table 3.** Values of soil quality indicators.

| No. | Soil quality indicators | Grachevsky dump (*n=20*) | | Shantobinsky dump (*n=20*) | |
|---|---|---|---|---|---|
| | | **Average** | **Standard deviation** | **Average** | **Standard deviation** |
| 1 | Hydrogen pH index | 8.40 | 0.32 | 8.15 | 0.88 |
| 2 | Organic matter, % | 0.82 | 0.27 | 1.08 | 0.32 |
| 3 | Nitrate nitrogen (N-NO3), million -1 | 2.80 | 0.00 | 2.80 | 0.00 |
| 4 | Mobile forms of sulfur, million -1 | 35.20 | 18.10 | 41.12 | 28.54 |
| 5 | Mobile phosphorus compounds, million -1 | 5.00 | 1.41 | 6.67 | 3.61 |
| 6 | Mobile compounds of potassium, million- 1 | 416.00 | 93.34 | 388.33 | 80.15 |
| 7 | Mineralization, ppm | 140.50 | 54.45 | 198.67 | 111.27 |
| 8 | Electrical conductivity mS/cm | 0.28 | 0.11 | 0.40 | 0.22 |

**Table 4.** Heavy metal content.

| No. | Element | Content, mg/kg (ppm) | | | |
|---|---|---|---|---|---|
| | | **Grachevsky dump (*n=20*)** | | **Shantobinsky dump (*n=20*)** | |
| | | **Average** | **Standard deviation** | **Average** | **Standard deviation** |
| 1 | Zn | 32.03 | 8.02 | 38.51 | 3.24 |
| 2 | Cu | 18.27 | 0.09 | 17.71 | 0.45 |
| 3 | Cd | 0.56 | 0.66 | 0.18 | 0.04 |
| 4 | Fe | 13,361.50 | 3,546.14 | 14,491.83 | 1,735.09 |
| 5 | Mn | 230.00 | 91.92 | 354.50 | 38.26 |
| 6 | Pb | 7.89 | 1.33 | 8.71 | 1.55 |

The temperature characteristics of the deposit regions are quite close.

However, it is necessary to note the differences in the values of indicators of climatic factors. The duration of the frost-free period in the air and on the soil differs by about 10 days. Accordingly, the duration of the growing season in the Shantobe area is less than in the Grachevsky field area. The sum of temperatures above 10 °C is also on average higher in the Grachevsky mine.

Moisture availability of the growing season by the moisture coefficient (K) is the same for both places and is equal to 1.14, which is optimal and stable. These regions are not considered as arid during the growing season. Indicators for moisture supply, humidity, and precipitation of the Grachevsky mine are also more favorable for the formation of vegetation cover. The total projective coverage (TPC) at the recultivated dump of the Grachevsky mine was 70%, and at the Shantobinsky mine was 56.6%. The TPC of the Grachevsky mine dump sites exceeded the TPC of the Shantobinsky mine sites (Figure 8).

Concerning the proximity to habitats with a certain water regime of plants on both dumps, one could observe a predominance of plants less demanding in terms of moisture content (xeromesophytes, mesoxerophytes) in the upper part of the dump. With a decrease in height to the base of the dump, the content of mesophytes increased.

**Table 5.** Climatic conditions in the areas where the deposits are located.

| **Indicator** | | **Deposit** | |
|---|---|---|---|
| **Climate indicators** | | **Grachevskoe** | **Shantobe** |
| **1. Total radiation and duration of a sunny day** | | | |
| Annual sum of total solar radiation (MQ), MJ/m$^2$ | with a clear sky | 5,900-6,100 | 6,100-6,500 |
| | under average cloud conditions | 4,100-4,600 | 4,600-5,000 |
| Monthly amounts of total radiation in clear skies, MJ/m$^2$ | June | 913 | 928 |
| | December | 92-121 | 121-148 |
| Average duration of a sunny day in the period May-July | | 9.9-10.6 hours | 9.9-10.6 hours |
| **2. Temperature characteristics** | | | |
| Average temperature, °C | July | 19.1 | 18.5 |
| | January | –14.9 | -16.2 |
| Sum of temperatures above 10 °C | | 2,000-2,300 | 2,000-2,200 |
| Duration of the frost-free period in the air | | 120-130 days | 110-120 days |
| Duration of the frost-free period on the soil | | 114 days | 102 days |
| Duration of the growing season | | 135-140 days | 130-135 days |
| Climate spring begins | | April 3-6 | April 3-7 |
| **3. Precipitation and moisture supply** | | | |
| Annual precipitation, mm | | 420 | 400 |
| Amount of precipitation for the warm period of the year | | 280-300 | 260-280 |

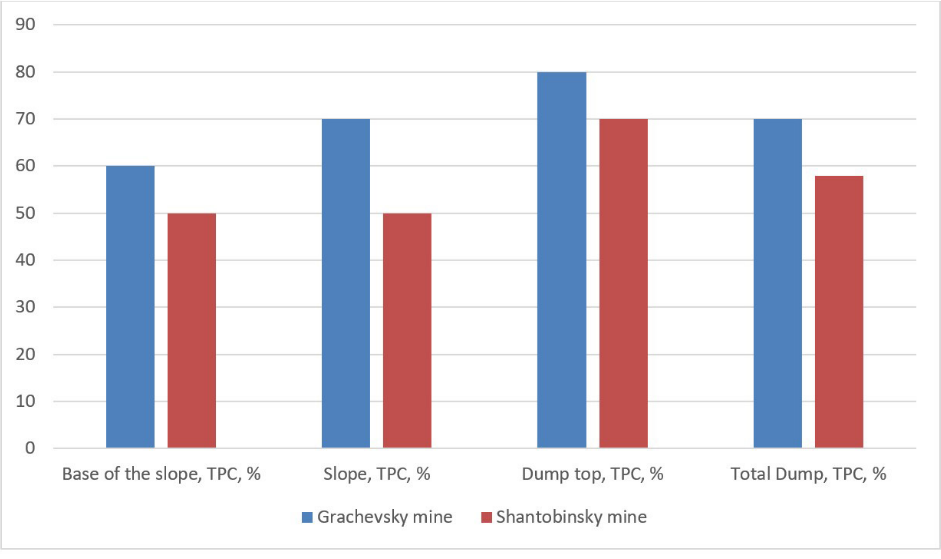


**Figure 8.** Projective covering of mine dumps.

This confirms the process of the natural distribution of moisture in the dumps when excess moisture tends to condense in lower places.

At the base of the slope of the Grachevsky mine dump, 50% of the 60% of the TPC had four species with a predominance of mesophytes. In the middle part, of the 70% of the TPC, 60% were represented by four species with a predominance of mesophytes. At the top, of 80% of the TPC, 70% was composed of three species with a predominance of xeromesophytes. In the upper part, there was a predominance of xeromesophyte plants that were less demanding in terms of moisture content. With a decrease in height on the way to the base of the dump, the content of mesophytes increased (Figure 9).

At the base of the slope of the dump of the Shantobinsky mine, of 40% of the TPC, 50% was composed of three species with a predominance of mesophytes and xeromesophytes. In the middle part, of 50% of the TPC, 40% were five species with a predominance of mesophytes and mesoxerophytes. At the top, of 70% of the TPC, 50% were formed by four species with a predominance of mesophytes, xeromesophytes, and mesoxerophytes. In the upper part of the dump, there was a predominance of mesoxerophyte plants that were less demanding in terms of moisture content (Figure 10).

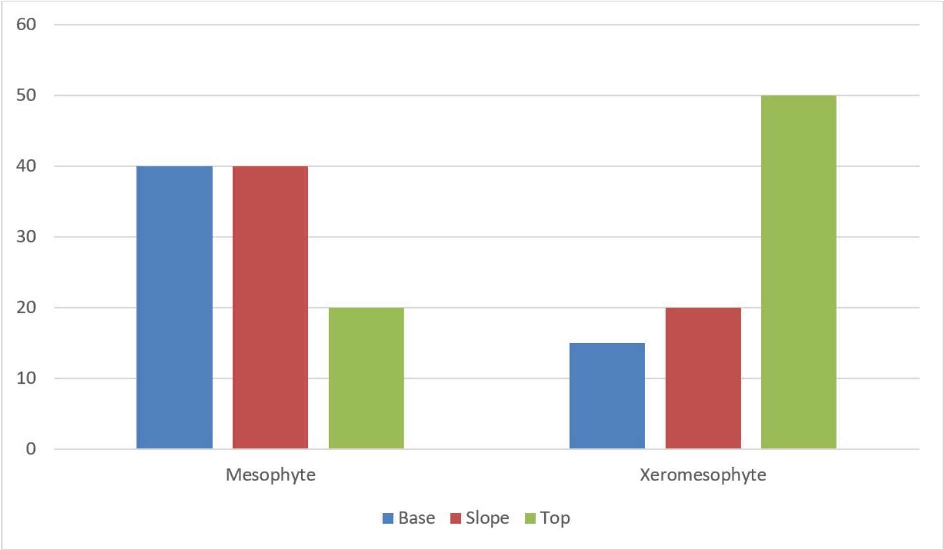


**Figure 9.** Distribution of plant TPC forming the maximum percentage of the projective covering of the Grachevsky mine dump, considering the ratio to the moisture potential in the soil.

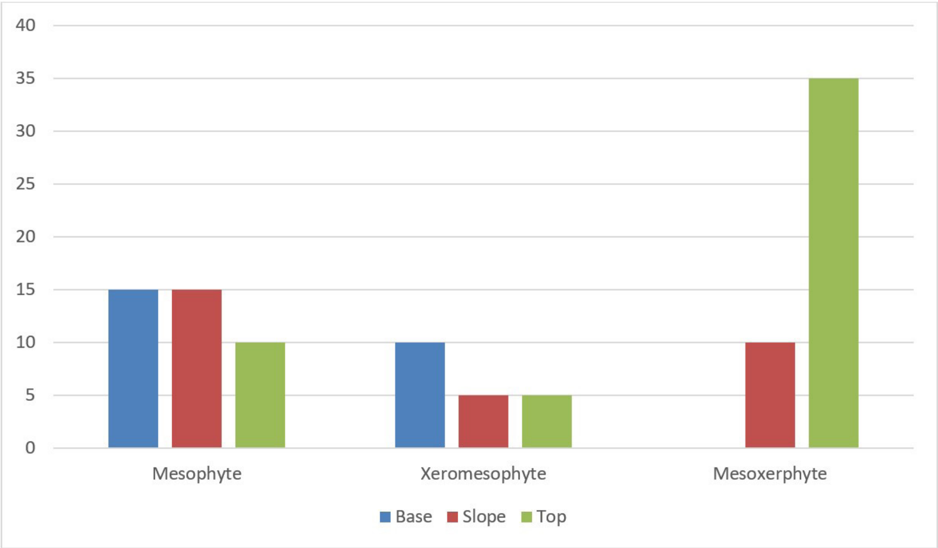


**Figure 10.** Distribution of plant TPC forming the maximum percentage of the projective covering of the dump of the Shantobinsky mine, considering the ratio to the moisture potential in the soil.

### *3.5. Characteristics of vegetation cover of the recultivated Grachevsky mine dump*

In total, 33 species were registered on the recultivated dump of the Grachevsky mine: 14 species at the base of the slope, 11 species in the middle, and 20 species at the top.

At the base of the slope, 50% of the 60% projective cover consists of four species: *A. absinthium* (10%), *B. inermis* (30%), *E. virgata* (5%), and *V. tenuifolia* (10%). In the middle part of the slope, out of 70% of the TPC, 60% consist of four species: *A. dracunculus* (10%), *E. repens* (30%), *E. virgata* (10%), and *Lathyrus pratensis* (10%). At the top of 80% of the projective cover, 70% consist of three species: *A. absinthium* (10%), *C. epigeios* (50%), and *C. setosum* (10%). The remaining species occur in small quantities or as single plants. Ruderal species make up 36% of the total number of species.

The TPC was 70%. The highest activity, above 10 points was demonstrated by six species: *A. absinthium* (27.4), *Euphorbia virgate* (18.2), *A. dracunculus* (15), *C. setosum* (15), *V. tenuifolia* (15), and *Poa angustifolia* (10.6) (Table 6, Figure 11).

The productivity of plant communities was 114.8±22.8 g/m$^2$. The coefficient of synanthrophization of flora was 57.8%.

**Table 6.** Characteristics of the vegetation cover of the recultivated dump of the Grachevsky mine.

| TPC, % | V, % | P, % | A, score |
|---|---|---|---|
| *A. absinthium* L. | 100 | 7.7 | 27.4 |
| *E. virgata* Waldst. & Kit. | 66 | 5 | 18.2 |
| *A. dracunculus* L. | 66 | 3.4 | 15 |
| *C. setosum* (Willd.) Besser | 66 | 3.4 | 15 |
| *V. tenuifolia* Roth | 66 | 3.4 | 15 |
| *P. angustifolia* L. | 66 | 1.7 | 10.6 |
| *Hieracium virosum* Pall. | 66 | 0.3 | 4.4 |
| *Taraxacum officinale* F.H. Wigg. | 66 | 0.3 | 4.4 |
| *Lathyrus tuberosus* L. | 66 | 0.3 | 4.4 |
| *Pastinaca sativa* L. | 33 | 0.2 | 2.6 |
| *Seseli libanotis* (L.) W.D.J. Koch. | 33 | 0.2 | 2.6 |
| *Achillea × kasakstanica* Kupr. et Kulemin | 33 | 0.2 | 2.6 |
| *Achillea millefolium* L. | 33 | 0.2 | 2.6 |
| *Artemisia armeniaca* Lam. | 33 | 0.2 | 2.6 |
| *Artemisia vulgaris* L. | 33 | 0.2 | 2.6 |
| *Centaurea pseudomaculosa* Dobrocz. | 33 | 0.2 | 2.6 |
| *Centaurea scabiosa* L. | 33 | 0.2 | 2.6 |
| *Cichorium intybus* L. | 33 | 0.2 | 2.6 |
| *Erigeron acris* L. | 33 | 0.2 | 2.6 |
| *Saussurea amara* (L.) DC. | 33 | 0.2 | 2.6 |
| *Lappula microcarpa* (Ledeb.) Guerke | 33 | 0.2 | 2.6 |
| *Berteroa incana* (L.) DC. | 33 | 0.2 | 2.6 |
| *Convolvulus arvensis* L. | 33 | 0.2 | 2.6 |
| *Astragalus onobrychis* L. | 33 | 0.2 | 2.6 |
| *L. pratensis* L. | 33 | 0.2 | 2.6 |
| *Medicago falcata* L. | 33 | 0.2 | 2.6 |
| *B. inermis* (Leyss.) Holub | 33 | 0.2 | 2.6 |
| *C. epigeios* (L.) Roth | 33 | 0.2 | 2.6 |
| *E. repens* (L.) Nevski | 33 | 0.2 | 2.6 |
| *Stipa lessingiana* Trin. & Rupr. | 33 | 0.2 | 2.6 |
| *Linaria vulgaris* Mill. | 33 | 0.2 | 2.6 |
| *Verbascum lychnitis* L. | 33 | 0.2 | 2.6 |
| *Veronica spicata* L. | 33 | 0.2 | 2.6 |

Note: TPC: total projective coverage, %; V: occurrence, %; P: partial projective coverage, %; A: activity, score.

*3.6. Characteristics of vegetation cover of the recultivated dump of the Shantobinsky mine*

30 species were registered on the recultivated dump of the Shantyubinsky mine: 23 at the base of the slope, 12 in the middle, and 15 at the top.

At the base of the slope, 40% of the 50% projective cover consisted of three species: *Agropyron cristatum* (5%), *A. absinthium* (15%), and *A. austriaca* (10%). In the middle part of the slope, out of 50% of the TPC, 40% consist of five species: *A. absinthium* (10%), *A. austriaca* (10%), *E. repens* (10%), *E. virgata* (5%), and *M. falcata* (5%). At the top of 70% of the projective cover, 50% consist of four species: *A. proceraeformis* (30%), *E. repens* (10%), *Artemisia austriaca* (5%), and *A. dracunculus* (5%). The remaining species occur in small quantities or as single plants.

The TPC is 56.6%. Productivity: 128.4 ± 25.6 g/m$^2$. The synanthropization of flora equaled 63.1%.

Based on the data presented in Tables 6 and 7 of the article, several plant species with notable activity scores have been identified within the recultivated dumps of the Grachevsky and Shantobinsky mines. These activity scores suggest the potential of these plant species to thrive and colonize these industrial waste areas effectively. Notably, *A. absinthium*, *A. austriaca*, *E. virgate*, and *A. dracunculus*, among others, exhibit activity scores exceeding 10 points, indicating their robust growth and potential resilience in these challenging environments. This resilience may be attributed to their ability to tolerate or bioaccumulate heavy metals and other chemical elements without detriment to their metabolic processes (Table 7, Figure 12).

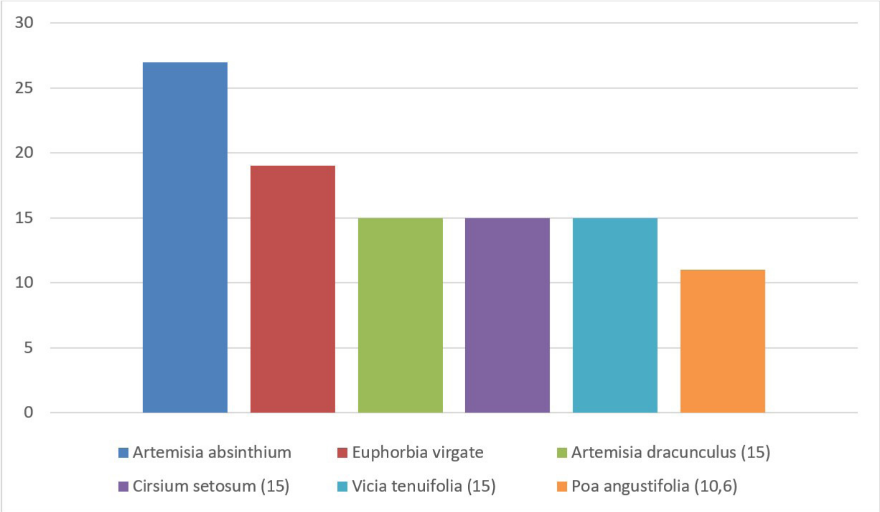


**Figure 11.** Distribution of species activity over 10 points.

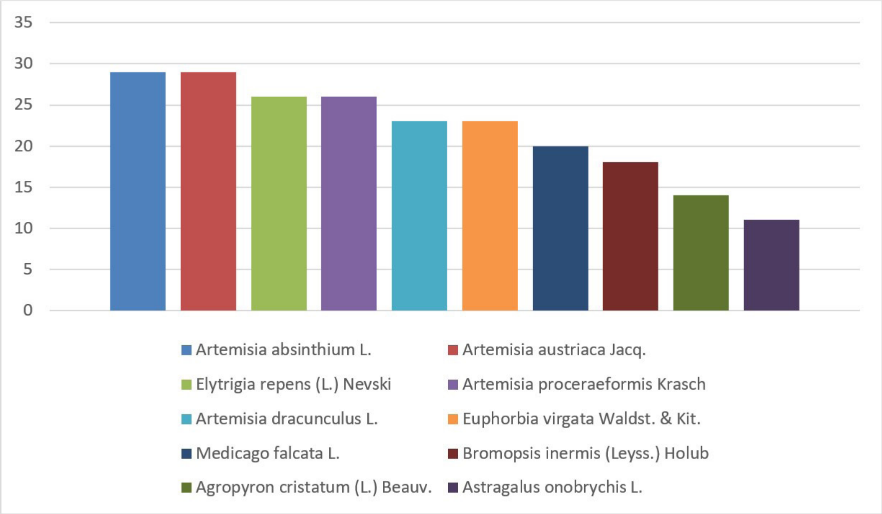


**Figure 12.** Distribution of species activity over 10 points.

The presence of these species is of particular importance for several reasons. First, their ability to bioaccumulate heavy metals and other chemical elements without harm to their metabolic processes can aid in the gradual detoxification of the soil over time, reducing ecotoxicity levels. Second, their colonization and establishment can help stabilize the soil, preventing erosion and further dispersion of contaminants. Third, these species may serve as pioneer plants, paving the way for the introduction of a more diverse plant community over time. Moreover, the choice of these species for artificial colonization efforts can potentially accelerate the reclamation process of uranium-containing waste dumps, especially in regions with similar climatic conditions.

Such families as *Asteraceae*, *Poaceae*, and *Fabaceae* are the predominant families in the species diversity on reclaimed dumps (Figure 13).

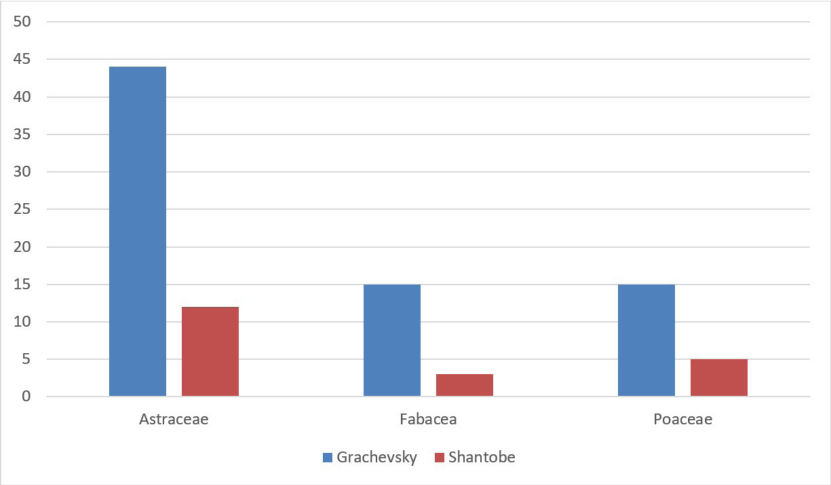


**Figure 13.** Percentage of species of Asteraceae, Poaceae, Fabaceae families on dumps.

**Table 7.** Characteristics of vegetation cover of the recultivated dump of the Shantobinsky mine.

| TPC, % | V, % | P, % | A, score |
|---|---|---|---|
| *A. absinthium* L. | 100 | 8.5 | 29.2 |
| *A. austriaca* Jacq. | 100 | 8.5 | 29.2 |
| *E. repens* (L.) Nevski | 100 | 6.7 | 25.9 |
| *A. proceraeformis* Krasch | 66 | 10.1 | 25.8 |
| *A. dracunculus* L. | 100 | 5 | 22.4 |
| *E. virgata* Waldst. & Kit. | 100 | 5 | 22.4 |
| *M. falcata* L. | 100 | 4.1 | 20.2 |
| *B. inermis* (Leyss.) Holub | 100 | 3.5 | 18.7 |
| *A. cristatum* (L.) Beauv. | 100 | 2 | 14.1 |
| *A. onobrychis* L. | 66 | 1.8 | 10.9 |
| *Potentilla argentea* L. | 66 | 1.3 | 9.3 |
| *Festuca valesiaca* Gaudin | 66 | 1 | 8.1 |
| *Achillea nobilis* L. | 100 | 0.5 | 7.1 |
| *C. arvensis* L. | 100 | 0.5 | 7.1 |
| *Lactuca tatarica* (L.) C.A. Mey. | 100 | 0.5 | 7.1 |
| *B. incana* (L.) DC. | 66 | 0.3 | 4.4 |
| *Carduus crispus* L. | 66 | 0.3 | 4.4 |
| *Nonea pulla* DC. | 66 | 0.3 | 4.4 |
| *Silene wolgensis* (Hornem.) Besser ex Spreng. | 66 | 0.3 | 4.4 |
| *Stipa capillata* L. | 66 | 0.3 | 4.4 |
| *Artemisia marschalliana* Spreng. | 33 | 0.2 | 2.6 |
| *A. millefolium* L. | 33 | 0.2 | 2.6 |
| *Artemisia scoparia* Waldst. & Kit. | 33 | 0.2 | 2.6 |
| *Senecio erucifolius* L. | 33 | 0.2 | 2.6 |
| *S. libanotis* (L.) W.D.J. Koch. | 33 | 0.2 | 2.6 |
| *T. officinale* F.H. Wigg. | 33 | 0.2 | 2.6 |
| *Tragopogon pratensis* L. | 33 | 0.2 | 2.6 |
| *Melilotus officinalis* (L.) Pall. | 33 | 0.2 | 2.6 |
| *Erysimum hieracifolium* L. | 33 | 0.2 | 2.6 |

Note: TPC: total projective coverage, %; V: occurrence, %; P: partial projective coverage, %; A: activity, score.

## 4. Discussion

During practical studies, for the first time, we carried out an assessment of the plant colonization processes at recultivated industrial waste dumps of the Grachevsky and Shantobinsky uranium deposits located in Northern Kazakhstan. We determined the plant species colonizing the dumps, the projective cover, the density of species, and the coefficient of synanthrophization. The productivity of the communities was 114.8-128.4 g/m$^2$. The formation of vegetation at the dumps is at the stage of thicket group communities.

Most of the climatic parameters of both mines were approximately the same but the values of temperature conditions and moisture supply of the Grachevsky mine were more favorable for the formation of vegetation cover compared to the Shantobe region. This is one of the factors that form a higher percentage of the projective coverage on the recultivated dump of the Grachevsky mine. We observed that the distribution of TPC of plants forming the maximum percentage of the projective cover at the dumps corresponded to the moisture potential in the soil. In the upper part of the dumps, there was a predominance of plants less demanding in terms of moisture content (xeromesophytes, mesoxerophytes). With a decrease in height to the base of the dump, the mesophyte percentage increases. This confirms the process of natural condensation of moisture in lower places.

A high degree of synanthropization indicates the incompleteness of the restoration processes of meadow and steppe communities characteristic of this climatic zone (Babkenov et al., 2023). The observed processes of vegetation cover formation reflect the most probable type of uranium mine waste dump colonization at low levels of radiation background. The studied processes of dump plant colonization do not contradict modern scientific publications (Bugubaeva et al., 2023; Nugmanov et al., 2022b).

During the study of the dumps, we noted that the average intensity of background ionizing radiation at the Grachevsky mine dump was 25-35 μR/hr and at the Shantobinsky mine 10-25 μR/hr, which meets the regulatory requirements for environmental safety. This level of ionizing radiation practically does not affect the formation of phytocenoses. Despite their very low radioactivity, dumps/tailings remaining after the extraction of uranium and the reclamation carried out need to be safely restored so that not only the radioactivity is effectively reduced but there is no danger to human health and biota.

The studied processes of vegetation cover formation on the dumps/tailings of uranium-containing waste from uranium mines do not contradict scientific publications and complement them in terms of the uniqueness of geographical and agro-climatic indicators of the studied objects, the features of the plant species composition, and the succession of plant groups (Barnekow et al., 2019; Bugubaeva et al., 2022; Hagen and Jakubick, 2011; Wen et al., 2004).

We identified plant species at the dumps that provide the most dynamic colonization and form the primary succession. Following the recommendations of the IAEA (Barnekow et al., 2019; IAEA, 2004) and modern studies (Hagen and Jakubick, 2011; Wen et al., 2004), these plant species can be used to carry out the processes of artificial colonization of spent dumps of uranium-containing waste, especially if it is necessary to accelerate the formation of a protective soil layer on the surfaces of reclaimed dumps in conditions of similar climatic zones. Six plant species, including *A. absinthium, E. virgate, A. dracunculus, C. setosum*, *V. tenuifolia*, and *P. angustifolia* have the greatest activity at the Grachevsky mine dump (above 10 points). At the dump of the Shantobinsky mine, 10 plant species have the highest activity of species (over 10 points), including meadow and steppe plants of six species *A. austriaca*, *A. proceraeformis*, *A. dracunculus*, *M. falcata*, *A. cristatum*, and *A. onobrychis* and four ruderal species *A. absinthium*, *E. repens*, *E. virgata*, and *B. inermis*.

According to the results of studies of agrochemical indicators of soil samples from dumps, it was found that, in general, such important indicators of potential soil fertility as humus, nitrogen, and phosphorus were relatively low and unfavorable for the formation of highly productive vegetation cover (Nasiyev et al., 2022b, 2023). To enhance the growth and intensification of the formation of the vegetation cover at the dumps, it is necessary to carry out measures to saturate the soils with mobile easily digestible forms of nitrogen and phosphorus compounds (Almanova et al., 2023). The potassium content is high enough and does not require additional work. The reduced humus content indicates the initial stage of the formation of the organic part of the soil. The potassium content is high enough and does not require additional work. The total form of the heavy metal content (zinc, copper, lead, manganese, cadmium, iron) in the studied soil samples generally meets regulatory requirements. We observed the excess of the total form of the cadmium content in the soil of the Grachevsky dump by about two times.

## 5. Conclusions

Recultivated dumps are a favorable ecotope for settlement and plant development. The observed process of dump colonization can be the most likely type of colonization of spent uranium-containing waste dumps at low levels of radiation background and relatively low indicators of nutrient content, considering the climatic characteristics of this region.

It is necessary to state the successful reclamation of the studied sites. Despite the incompleteness of the syngenesis process, this technology of recultivation of uranium mine waste dumps is effective for reducing the background of ionizing radiation, isolating waste, and protecting dumps from natural erosion processes. It can be successfully used for the recultivation of uranium-containing industrial waste dumps at uranium deposits.

In conclusion, this research has shed light on the crucial aspects of plant community development, ionizing radiation, agro-climatic influences, and soil characteristics on recultivated dumps containing spent uranium-containing waste from uranium mines. The findings not only contribute to understanding of ecological restoration in uranium mining areas but also hold practical significance by providing insights into the successful establishment of vegetation cover, which is vital for environmental safety and long-term stability of such sites. This knowledge can inform future reclamation efforts, ensuring the protection of ecosystems and human health in regions affected by uranium mining activities.

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