International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

Studies of Soils from Kuzbass Coal Mines for Recultivation Measures

Svetlana Ivanova [1,2], Anna Vesnina [1], Nataly Fotina[1], Alexander Prosekov [3]*

[1]*Natural Nutraceutical Biotesting Laboratory, Kemerovo State University, 6 Krasnaya str., Kemerovo, 650043, Russia.*

[2]*Department of TNSMD Theory and Methods, Kemerovo State University, 6 Krasnaya str., Kemerovo 650043, Russia.*

[3]*Laboratory of Biocatalysis, Kemerovo State University, 6 Krasnaya str., Kemerovo 650043, Russia.*

Abstract

Recultivation of technologically disturbed lands is a critical objective of environmental protection. An important stage of recultivation is the biological stage – the application of living organisms for soil restoration. The purpose of the study is to explore the agrophysical, agrochemical, and biochemical characteristics of soil samples from the coal mine dumps and experimental fields of of Kuzbass, Russia chosen for the study. The research is also aimed at developing biorecultivation measures to restore environmental indicators considering the characteristics of the regions in question. The results demonstrate that soil pollution indicators are within the norm except for elevated arsenic, cadmium, nickel, cobalt, chromium, and manganese levels and reduced nutrient levels. Based on the obtained data, the soils are classified as suitable for the biological recultivation stage.

Keywords: Coal mining, coal mine, recultivation, biorecultivation, pollution

Full length article **Corresponding Author*, e-mail: pavvm2000@mail.ru

1. Introduction

The mining industry, coal mining included, has a profound detrimental effect on the ecosystem, reducing the area of agricultural and other lands, as well as the diversity of flora and fauna [1], and shortening the healthy life expectancy of residents. Recultivation of technologically disturbed lands is a critical task in the framework of environmental protection [2]. The primary need for recultivation consists in restoring the value of disturbed lands, improving the ecological conditions of the area, and creating harmonious landscapes that satisfy ecological, economic, aesthetic, and sanitary-hygienic requirements [3, 4]. Contemporary industrial development needs to be oriented on maintaining a responsible and respectful attitude to nature [5] and avoiding disrupting the carbon balance in line with the 2015 Paris Climate Agreement [6]. Scientific research begins to focus on scenario projections of the ratio of ecological (carbon) footprint and biocapacity of territories by 2050, monitoring and accounting of pollutant emissions into the atmosphere, carbon sequestration by various natural systems, creation of carbon farms and landfills, inventory of greenhouse farms, and gas emissions in managed forests. Apart from atmospheric pollution, coal mining majorly disturbs the landscape, which entails the disruption of biocenosis [7]. Open pit mining removes fertile soil together with overburden and destroys forests, meadows, and agricultural lands [8]. The resulting dumps put heavy pressure on the ground. Consequently, surface groundwater recedes, and soils and fields dry up [9, 10]. The dumps themselves occupy considerable areas, where native flora and fauna disappear entirely, and the soil becomes unfit for farming. The exposed areas undergo wind and water erosion of soils [11], which results in soil loss, gully formation, emergency situations, and deterioration of the aesthetic appearance of the sites [12]. In view of the above, recultivation of lands and measures to combat and prevent pollution and erosion processes are critical tools for restoring the natural environment [13]. The choice of these instruments has to be made with consideration of regional soil and climatic conditions, the state and degree of natural overgrowth of disturbed lands, agrochemical and agrophysical properties of soils and rocks, industry development prospects, the possibility of reoccurring disturbances, and other factors.

One of the most vital steps of recultivation is the biological stage, which involves the application of biological organisms in restoration measures [14]. The intended result of the biological recultivation of disturbed industrial lands (industrial dumps) is the creation of stable productive and economically valuable biocenoses on them [12]. Greenery can solve a variety of problems caused by the coal mining industry [15]. Plants restore disturbed landscapes, while also reducing carbon footprint [16]. However, the natural overgrowth of dump envelopes cannot ensure quality restoration of the flora characteristic of the given phytogeographic zone [17]. Therefore, there is a need to develop fundamentally new methods for the recultivation of vegetation cover to restore the pre-mining floristic

diversity of territories [18]. Thus, the paradigm of today's stage of disturbed land recultivation consists in restoring the vegetation cover that can maintain and support a stable level of biodiversity [12, 19].

The purpose of the present study is to investigate the agrophysical, agrochemical, and biochemical properties of soil samples collected from coal mine dumps and experimental fields in Kuzbass, Russia chosen for the study. Furthermore, the research is aimed at developing biorecultivation measures to restore environmental indicators considering the characteristics of the regions.

2. Methods

2.1. Research materials

2.1.1. Objects of research

The objects under study are several territories in the Kemerovo Region – Kuzbass: the coal mine 1and the coal mine 2, which are located in the west and south of the Kemerovo Region (Fig. 1).

Figure 1. Map of the Kemerovo Region and the studied coal mines: 1 – the coal mine 1; 2 – the coal mine 2.

2.1.2. Chemical reagents and equipment

All standards and reagents were supplied by AG Analytekspert, Russia and were at least of the chemically pure grade. All spectrophotometric measurements were performed using a microplate reader CLARIOstar (BMG Labtech, Germany). Measurements of pH were performed using a PH-98 pH/OPP meter with a temperature sensor (Amtast, China). Drying was carried out in a drying oven IKA Oven 125 basic dry-glass (LOIP JSC, Russia) and in a muffle furnace LF-2/13-G1 (LOIP JSC, Russia). Infrared spectrometry was performed on a TIDAS P 900 NIR (PharmaTest, Germany). Atomic absorption analysis was conducted using a ZEEnit 650 Atomic Absorption Spectrophotometer (Analytik Jena GmbH, Germany). Gas chromatography was conducted using a gas chromatograph Crystal 5000 p.2 with an EZD detector (Chromatek, Russia).

2.2. Research methods

2.2.1. Soil sampling

The collection of soil samples from technologically disturbed and undisturbed territories (coal mine dumps) of the Kemerovo Region (53°46″ N, 87°44″ E) was performed in accordance with GOST 17.4.4.02-2017 [20]. Five zones were allocated within the studied soil areas, and four parallel soil samples were taken in each zone. Sampling was carried out using the envelope principle: samples were taken from the corners and the center of the area under study (vegetation cover was removed beforehand). The depth of sampling was 0-10 cm, and the mass of sampled material was 0.5-1.0 kg. The collected samples were placed in a 50x50 cm polyethylene bag and then mixed to create a combined sample. Samples were taken at five different points in the studied land plot, meaning that a total of 20 samples were collected from each territory. The tool used to collect soil samples was a stainless-steel sampling scoop. The storage temperature was 4±2°C. Prior to analysis, organic inclusions (roots, branches, leaves, etc.) and large aggregates were removed from the sampled soil. To obtain an air-dry condition, the soil was spread on a clean paper in a layer not exceeding 1.0 cm and dried at room temperature, stirring occasionally. The resulting air-dry mass was grinded in a porcelain mortar and sieved (sieve pore area no more than 1 mm^2). Samples from the coal mine 1 were designated as Samples 1, and those from the coal mine 2 – as Samples 2. As negative control [21-23], we examined soil samples from a forest plot (54°17″ N, 87°15″ E), marked as Samples 3. The soil samples whose characteristics were used as negative control (background values) in the study of technologically disturbed lands were taken 10-100 km away from the sampling sites of the main study areas. The chosen forest areas were located in the Erunakovskoe and Elovskoe forestries. In terms of administrative and territorial location, they belong to the Novokuznetsk (Krasulinskoe Rural Settlement) and Prokopevskoe (Bolshetaldinskoe Rural Settlement) municipal districts.

2.2.2. Determination of total nitrogen content

Total nitrogen content (%) was determined using the method described in GOST R 58596 [24]. To prepare solution A, 56.7 g of sodium salicylic acid, 16.7 g of potassium sodium tartaric acid, 26.7 g of sodium hydroxide, and 0.4 g of sodium nitroprusside were dissolved in 1 l of water. Solution B was prepared by adding 1,750 ml of distilled (d.) water without ammonia, 250 ml of sodium hydroxide solution with molar concentration C(NaOH)=2 mol/l, and 4.5 g of Trilon B to 250 ml of solution A. To obtain Solution C, 150.0 g of bleach and 105.0 g of sodium carbon dioxide were added to 510 ml of d. water, then the upper clear layer was diluted with d. water without ammonia to a mass concentration of free chlorine of 0.12 g per 100 ml. Next, to a 0.2 g sample of soil, 2 ml of 30% hydrogen peroxide and 3 ml of a solution of 1 g of selenium dissolved in 200 ml of concentrated (concentrated) sulfuric acid were added, then stirred, and heated to 400°C until the solution was completely discolored. The resulting solution was cooled and brought up to 50 ml with water. To conduct the

analysis, 45 ml of solution B and 2.5 ml of solution C were added to 1 ml of the obtained solution. After a 1 hour wait for the formation of stable coloring, the optical density was measured relative to the zero solution in a cuvette with a 1 cm thick absorbing layer at a wavelength of 655 nm.

Total soil nitrogen content (N_f) in percent was calculated using the formula:

$$N_f = \frac{a \cdot V_1 \cdot 100}{V_2 \cdot m \cdot 1000} = \frac{a \cdot V_1}{V_2 \cdot m \cdot 10}$$

where a – the amount of nitrogen in the analyzed volume plotted on a graph, mg; V_1 – the total volume of the solution after soil disintegration, ml; V_2 – the volume of the solution taken for analysis, ml; m – the mass of dry soil, g; *100* – conversion factor to percentage; *1,000* – mg to g conversion factor.

2.2.3. Determination of ammonium nitrogen content

Determination of ammonium nitrogen content (mg/kg) was carried out according to PND F 16.2.2:2.3:3.30-02 [25]. Soil in a volume of 100 cm^3 was pulverized, 100 ml of ammonia-free water was added, and the mixture was filtered through a paper filter. Depending on the content of ammonium nitrogen in the filtrate, 1.0-80.0 ml of the solution were sampled and, if necessary, brought to 80 ml with ammonia-free water. Next, 1 ml of Segnet salt solution (50.00 g of potassium sodium tartaric acid per 100 ml of water) and 1 ml of Nessler's reagent were added, the solution was stirred, and its volume was brought up to 100 ml with ammonia-free water. After 10 minutes, the optical density of the solution was measured in cuvettes with an optical layer thickness of 3 cm, at λ=(400±5) nm in relation to the blank sample (ammonia-free water treated under the same conditions as the analyzed sample).

The mass fraction of ammonium ions (NH_4^+), mln^{-1} (mg/kg) by dry matter in samples with moisture content less than 90 % was calculated using the formula:

$$X_{NH_4} = \frac{K \cdot D \cdot 1000 \cdot V_2}{m_1 \cdot (1 - W) \cdot V_1}$$

where D – optical density on the photocolorimeter scale; K – calibration factor; $m_1(1 - W)$ – the mass of the dry matter taken for analysis with consideration of moisture content, g; V_1 – the volume of the sample (water extract) taken for photocolorimetry, ml; V_2 – the volume of ammonia-free water taken to bring the moisture content of the sample to 90%, ml.

2.2.4. Determination of nitrate nitrogen content

Nitrate nitrogen content (mg/kg) was estimated in accordance with PND F 16.1:2:2.2:3.67-10 [26]. 0.05% potassium sulfate was added to 5 g of soil and filtered. Depending on the expected nitrate ion content, 5-10 ml of the soil extract was taken and evaporated. After cooling, the dry residue was mixed with 2 ml of concentrated sulfuric acid and left for 10 minutes. Then the contents were diluted with 10-15 ml of d. water, 15 ml of a solution of sodium hydroxide and Segnet salt (400 g sodium hydroxide and 60 g Segnet salt per 1 l of d. water) were added, the d. water was brought to 50 ml, and photometry was carried out at 410 nm. Nitrate nitrogen content (mln^{-1}) was calculated using the formula:

$$X = K \cdot \frac{C \cdot V_1 \cdot V_3}{V_2 \cdot a} \cdot n \cdot 0{,}23$$

where X – nitrate nitrogen content in the sample, mln^{-1}; C – concentration of nitrate ions by the calibration graph, mg/l; V_1 – the total volume of the extract (50 ml); V_2 – the volume of aliquot taken for analysis, ml; V_3 – test tube capacity, 10 ml; a – sample weight, g; K – conversion factor to absolutely dry sample; n – dilution factor; *0.23* – conversion factor of nitrate ions to nitrate test.

2.2.5. Determination of organic matter content

Organic matter content (%) was measured in accordance with GOST 26213 [27]. The mass of the soil sample was determined based on the expected content of organic matter. 10 ml of chromium mixture (40 g potassium bromide per 1 l of water and 1 l of concentrated sulfuric acid) were added to the samples and heated for 1 h in a water bath. After cooling, 40 ml of water was added to the sample, and the resulting mixture was filtered through an ash-free paper filter. Spectrophotometry was carried out at 590 nm. The mass fraction of organic matter was calculated according to the formula:

$$X = \frac{m \cdot K}{m_1} \cdot 100$$

where m – the mass of organic matter in the sample, mg; K – correction factor for the concentration of the reducing agent; m_1 – the mass of the sample, mg; *100* – the conversion factor into percentages.

2.2.6. Determination of moisture content

Soil moisture content (%) was determined according to PND F 16.1:2.2:2.3:3.58-08 [28]. A 20 g soil sample was evaporated until dry in a boiling water bath, dried at 105°C for 30 minutes, and then weighed. The mass fraction of moisture in the sample X, %, was calculated using the formula:

$$X = \frac{(m_1 - m_2) \cdot 100}{m}$$

where m_1 – the mass of the cup with the moist sample, g; m_2 – the mass of the cup with the dry sample, g; m – the mass of the analyzed sample, g.

2.2.7. Determination of soil density, porosity, and moisture capacity

Determination of soil density, solid phase density, porosity, and water holding capacity was carried out according to GOST R 53380-2009 [29]. Hygroscopic moisture content was determined by drying 5 g of the sample in a closed bouquet at 100°C, cooling in a desiccator, and weighing using the formula:

$$W_r = (M_3 \cdot 100) \,/\, M$$

where M_3 – the mass of evaporated water, g; M – the mass of dry soil.

The volumetric mass was determined by weighing the ungrounded sample in a metal cylinder. Soil moisture was determined at the same time. The height of the layer of soil put in was measured, and the diameter of the cylinder and the volume of soil were determined. The cylinder with soil was weighed with the error of change +0.01 g and the necessary calculations were carried out. The volumetric mass d_2 of greenhouse soil, g/ml, was found using the formula:

$$d_2 = M/V$$

where M – the mass of dry soil in the cylinder, g; V – the volume of the cylinder, ml.

The mass of dry soil M, g, was calculated using the formula:

$$M=M_4*100/(100+W_0)$$

where M_4 – the mass of moist soil in the cylinder, g; W_0 – soil moisture, %.

The cylinder volume V, cm^3, was identified using the formula:

$$V=3.14*r2*h$$

where r – cylinder radius, cm; h – cylinder height, cm.

The final formula for the calculation is as follows:

$$d_2=M_4\text{-}100/(100+W_0)V$$

The density of the solid phase was determined in air-dry soil using the pycnometer method. Cooled d. water was poured into a pycnometer up to 100 ml. From the sample sieved through a millimeter sieve, 5 g of air-dry soil was weighed. A little more than 1/2 the volume of d. water was poured out of the weighed pycnometer and the soil suspension was poured into it. The beaker containing the soil was weighed again and the difference was used to find the mass of the soil taken to determine the density of the solid phase. The pycnometer with water and soil was boiled for 30 min, adding water as it boiled off to half of its volume. After boiling, the pycnometer was cooled to room temperature, filled to the mark with cooled water, wiped outside with filter paper, and weighed on analytical scales. The temperature of the pycnometer with water and soil and the original temperature of the pycnometer with water were the same. The density of the solid phase of the soil D, g/cm^3, was calculated using the formula:

$$D=M_5/(M_6+M_5)–M_7$$

where M_5 – the mass of the dry soil sample, g; M_6 – the mass of the pycnometer with water, g; M_7 – the mass of the pycnometer with water and soil, g.

$$M_5=M_8*100/100+Wr$$

where M_8 – the mass of the air-dry soil sample, g; W_r – hygroscopic moisture content of greenhouse soil, %.

The volume of pores occupied by water at the moment (water holding capacity) W2, %, was calculated according to the formula:

$$W2=W_0d_2$$

where W_0 – soil moisture, %; d_2 – volumetric mass of the soil, g/cm^3.

Air capacity (aeration porosity) W_2, %, was calculated using the formula:

$$W_2=P\text{-}W_1$$

where P – total porosity of the greenhouse soil, %; W_1 – water holding capacity of the greenhouse soil, %.

The value of total soil porosity P, %, was calculated from the ratio of solid phase density and soil volumetric mass using the formula:

$$P=100(1–d_2/D)$$

where d_2 – the volumetric mass of the soil, g/cm^3; D – density of the solid phase of the soil, g/cm^3.

2.2.8. Determination of dry residue

Determination of dry residue was carried out according to GOST R 59540-2021 [30]. A suspension of dry soil was placed in a conical flask and filled with five times the amount of d. water (in the ratio of 1:5). The mass of the suspension was determined based on the number of parameters to be tested. The contents of the flask were stirred and then the suspension was filtered. The filtrate in an amount of 5 to 50 ml was evaporated in a water bath with d. water in a porcelain cup dried to a constant mass in advance. Then it was placed in a desiccator at 110°C and dried to a constant mass, cooled in the desiccator, and weighed.

Dry residue S, %, was calculated according to the formula:

$$S=(a*V*100)/(Vnp*p)$$

where a – the weight of dry residue, g, V – the volume of the whole extract, ml; Vnp – the volume of the extract sample taken for analysis, ml; p – sample of absolutely dry soil, g.

2.2.9. Determination of ash content

Ash content was determined following GOST 27784-88 [31]. Samples were placed in pre-weighed porcelain crucibles so that the soil occupied no more than 2/3 of the crucible volume, weighed, and heated in a desiccator to 105°C. The crucibles with samples dried to constant weight were put in a cold muffle furnace, the temperature was gradually brought to 525°C, and the crucibles were calcined for 3 hours. The crucibles with ash residue were removed from the muffle furnace, cooled in the desiccator, and weighed.

The mass fraction of ash content was calculated using the formula:

$$A=(m\text{-}m_1)/m_2*100$$

where m – the mass of the crucible with ash residue, g; m_1 – the mass of an empty crucible, g; m_2 – the mass of dry soil, g.

2.2.10. Determination of moisture, maximum hygroscopic limit, and wilting moisture

The tests were performed in accordance with GOST 28268-89 [32]. Soil moisture was determined by placing soil samples into dried and weighted cups with lids. The soil was dried to a constant mass at 105°C in a desiccator. The time of drying until the first weighing was 5 hours, and the time of further drying was 2 hours. After each drying period, the cups with soil were covered with lids, cooled in a calcium chloride desiccator, and weighed with an error of no more than 0.1 g. Drying and weighing were stopped if the difference between repeated weighing did not exceed 0.2 g.

The mass ratio of moisture in soil (%) was calculated according to the formula:

$$W=(m_1-m_0)/(m_0-m)*100$$

where m_1 – the mass of moist soil with the cup and lid, g; m_0 – the mass of dried soil with the cup and lid, g; m – the mass of an empty cup with the lid, g.

Maximum hygroscopic soil moisture was determined by placing samples in pre-dried and weighed cups, selecting the diameter of the cups so that the soil layer in them did not exceed 4 mm. Cups with soil without lids were placed in the desiccator with a saturated potassium sulfate solution to saturate the soil with water vapor. The first weighing of cups with soil was performed 15 days after the start of saturation. Weighing was repeated every 5 days. Soil saturation with moisture was considered complete if the difference in masses between repeated weighing was no more than 0.005 g. The formula for calculations was the same as for determining moisture content.

The method for determining the moisture level of stable wilting of plants involved a tracking scheme. The soil taken for analysis was placed in glass beakers. Cotton plants were grown on it at 20% moisture content. Irrigation of soil up to the specified level was first performed with a nutrient mixture (per 5 l of water – 2.03 g of monoammonium phosphate, 3.88 g of ammonium nitrate, 2.68 g of potassium nitrate) at 50 ml per beaker and then with clean water and controlled by the weight of the beaker with soil. Overlapping seeds with germinated roots no longer than half a grain were planted in moistened soil in the amount of 5 pcs. per cup at a depth of about 0.5 cm. When seedlings appeared, the plants were placed in glasses under artificial light with an intensity of 5,000 lx for 16 hours a day. Weighing was carried out daily. Watering with water to the optimum humidity was carried out periodically. After the emergence of the first leaf, two plants out of five were removed, leaving the three most developed ones. When the cotton plants reached the phase of the third true leaf development, holes were cut in tracing paper circles made to the size of the cup, the plants were inserted into them, and the tracing paper circles were placed on the soil surface so that the edges of the tracing paper did not touch the sprouts. After that, sand was poured on the circles in an even layer 3 cm thick. As soon as plants with reduced turgor on all leaves were noticed during the observation, they were moved to an exicator, where the air humidity was close to saturation, and left overnight. If by morning the plant restored turgor on at least one leaf, the glass was returned under artificial light. If turgor was not restored on any leaf by morning, the soil in this beaker had reached the stable wilting moisture. The beaker was then disassembled the same day, and the plant, sand, tracing paper, and the upper 2 cm of soil were removed. The moisture content of the remaining soil was determined, and this was the moisture content of the stable wilting of the plant. The formula for calculations was the same as for determining moisture content.

2.2.11. Determination of pH

Salt and water pH values were determined according to GOST 26483 [33]. To the samples of soil weighing 30 g, 75 ml of extraction solution (KC1 1 mol/L (1n.), pH 5.6-6.0) was added. A sample without soil was taken as a negative control. Soil with the solution was stirred for 1 min and its pH was measured.

2.2.12. Determination of total alkalinity

Total alkalinity was determined according to PND F 16.2.2:2.3:3.31-02 [34]. 100 ml of water filtrate of the analyzed sample was taken with a measuring flask, placed in a beaker for titration, and blown with air for (2-3) minutes. Next, it was titrated with a hydrochloric acid solution with a molar concentration of 0.1 mol/l until pH=(4.5±0.1) under constant stirring. The solution was again blown with air for 2 minutes, and if the reading of the instrument changed, it was titrated again and measured. Calculation of total (M) alkalinity, mg-equiv/l, was performed according to the formula:

$$M = \frac{V_2 \cdot N \cdot K \cdot 1000}{V_{np}}$$

where V_1 – the volume of hydrochloric acid solution used for titration to pH=8.3 from the initial pH value, ml; V_2 – the volume of hydrochloric acid solution used for titration to pH=4.5 (3.5) from the initial pH value, ml; N – molar (normal) concentration of hydrochloric acid solution, mol/ml (g-equiv/l, n.); K – correction factor for hydrochloric acid solution; V_{np} – the volume of the sample taken for analysis, ml.

2.2.13. Determination of hydrolytic acidity

Determination of hydrolytic acidity (mol/100 g) was carried out according to GOST 26212 [35]. Soil samples weighing 1 g were placed in flasks, and 150 ml of sodium acetic acid solution (CH_3COONa) at a concentration of 1 mol/l was added. The soil with the solution was stirred for 5 min and left for 20 hours. The soil was shaken before the pH measurement. The pH values were recorded no earlier than 1 minute after the immersion of electrodes. Hydrolytic acidity was determined according to the table of values presented in GOST 26212 [35].

2.2.14. Determination of specific electrical conductivity

Specific electrical conductivity (mS/cm) was measured according to GOST 26423-85 [36]. To a soil sample of 30 g, 150 ml of d. water was added and stirred. After 5 min of settling, a conductometer sensor was

immersed in the suspension and the electrical conductivity and temperature were recorded. The resulting suspension was used for pH measurement and then filtered through paper filters. The specific electrical conductivity of the analyzed extract (X), mS/cm, was calculated using the formula:

$$X=a*C*k$$

where *a* – the determined electrical conductivity of the extract, mS; *C* – constant of the conductometric cell (sensor), cm^{-1}; *k* – temperature correction factor to bring the electrical conductivity measured at the given temperature to 25°C.

2.2.15. Determination of cation exchange capacity

Determination of cation exchange capacity (mol/100 g) was carried out according to FR.1.31.2020.38220 [37]. To a 2.50 g soil sample, 50 ml of magnesium acetic acid solution with ($Mg(CH_3COO)2$)=0.25 mol/dm^3 with pH=7.0 was added and shaken for 30 min. The settled solution was filtered, 50 ml of magnesium acetic acid solution with ($Mg(COO)_2$)=0.5 mol/l was added, and the solution was shaken on a rotator for 15 min. The soil suspension was allowed to settle for 5 min, after which the solution above the soil was carefully removed onto a filter. Then 50 cm^3 of magnesium acetic acid solution with ($Mg(CH_3COO)2$) = 0.025 mol/dm^3 were added to the soil again, shaken, then the solution was transferred to the same filter, the soil residue was washed onto the filter with no more than 120 ml of water. Then 100 ml of potassium chloride (KCl)=0.5 mol/dm^3 solution was poured onto the filter with soil in portions. In the filtrate, the magnesium content, which is equivalent to the cation exchange capacity, was determined on an atomic absorption spectrophotometer by rotating the burner tip by 30° relative to the light beam of a lamp with a full cathode on the analytical line of 285.2 nm. After this, 2 ml of filtrate obtained by treatment of the soil sample with potassium chloride solution was placed in technological containers, and 48 ml of solution with a mass concentration of strontium at 2.08 mg/cm^3 was added to it and mixed. The analyzed solutions were injected into the air-acetylene flame of the atomic absorption spectrophotometer, and the readings of the instrument were recorded.

2.2.16. Determination of the sum of absorbed bases

The sum of absorbed bases (mmol/100 g) was determined according to GOST 27821-88 [38]. To soil samples weighing 10 g each, 50 ml of hydrochloric acid solution was added, stirred for 1 h on a rotator, and left for 24 h. Next, 25 ml of settled liquid was taken for analysis and titrated with sodium hydroxide solution (NaOH 0.l mol/L (0.1 n)) under constant stirring. An equivalent point value of 8.2 pH and a holding time of 30 s was set on the automatic titration unit. The titration of 25 ml of hydrochloric acid solution was carried out similarly. The sum of absorbed bases in millimoles per 100 g of soil was calculated using the formula:

$$S = \frac{(V_0 - V) \cdot c \cdot 100}{m}$$

where *Vo* – the volume of sodium hydroxide solution consumed for titration of the hydrochloric acid sample, ml; *V* – the volume of sodium hydroxide solution consumed for titration of the extract sample, ml; *c* – concentration of sodium hydroxide solution, mmol/l; *100* – conversion factor to per 100 g of soil; *m* – the mass of the soil sample corresponding to the volume of extract taken for titration, g.

2.2.17. Determination of the content of chloride ions, sulfate ions, carbonate ions, bicarbonate ions, and sodium, calcium, and magnesium ions

The contents of chloride ions, sulfate ions, carbonate ions, bicarbonate ions, and sodium, calcium, and magnesium ions were determined according to FR.1.31.2021.38757 [39]. The content of carbonate and bicarbonate ions was measured as follows. To 10 g of soil, 150 ml of d. water was added, the mixture was stirred, and the extract was filtered through a paper filter. After this, 20 ml of water extract was taken and placed on a magnetic stirrer. A burette was filled with sulfuric acid solution at a concentration of 0.02 mol/l. An electrode pair was immersed in the sample to measure the end point of titration equal to 8.3. The stirrer was switched on, and titration of pH 8.3 was started. The volume of consumed acid was measured. Then titration continued up to pH 4.4, and the acid consumption rate in the burette was recorded.

The amount of carbonate ion equivalents (X), mmol per 100 g of soil, was calculated according to the formula:

$$X = \frac{2 \cdot c \cdot V \cdot 500}{V_1}$$

where *2* – coefficient indicating that at pH 8.3, the carbonate ion is half-titrated; *c* – concentration of the sulfuric acid solution with (1/2 H2S04) mmol/ml; *V* – the volume of sulfuric acid solution consumed for titration of the sample to pH 8.3, cm3; *500* – conversion factor to mmol/100 g of soil; V_1 – the volume of the extract sample, ml.

The amount of bicarbonate ion equivalents (L), mmol per 100 g of soil, was determined according to the formula:

$$X = \frac{c(V_1 - V) \cdot 500}{V_2}$$

where *c* – concentration of sulfuric acid solution, mmol/ml; V_1 – the volume of sulfuric acid solution consumed for titration of the sample from pH 8.3 (or lower if carbonate ion is absent) to pH 4.4, cm3; *V* – the volume of sulfuric acid solution consumed for titration of the sample to pH 8.3, ml; *500* – conversion factor to mmol/100 g of soil; V_2 – the volume of the extract sample, ml.

Chloride ions in a water extract of soil were determined as follows. To 100 g of soil, 1 l of water was added. The mixture was stirred and filtered through a paper filter. Next, 20 ml of it was taken into a chemical beaker, and electromotive force was determined. The concentration of chloride ions was determined based on a calibration graph.

Determination of sulfate ions in the water extract of soil was carried out as follows. One liter of d. water was

added to 100 g of soil and stirred, and the extract was filtered through a paper filter. To 20 ml of the filtrate, 50 ml of d. water and 10% barium chloride solution were added until sulfate ions were completely precipitated. The solution was evaporated in a water bath. The dry residue was dissolved in hydrochloric acid, filtered through a paper filter, and washed with a hydrochloric acid solution. Then it was transferred to a pre-weighed crucible and placed in a muffle furnace for 30 minutes at 700ºC. The amount of sulfate ions was calculated according to the formula:

$$X = \frac{(m - m_1) * 500}{116.7 * V}$$

where m – the mass of the crucible with residue, mg; m_1 – the mass of an empty crucible, mg; *500* – conversion factor to per 100 g of soil; *116.7* – the molar mass of barium sulfate equivalent, mg/mmol; V – the volume of the sample extract, ml.

Measurement of the ions of potassium, calcium, magnesium, and sodium was carried out as follows. To 2 g of soil, 10 ml of nitric acid with a molar concentration of 0.5 mol/l was added. The resulting suspension was stirred and incubated at 90ºC and stirred for 3 hours. Then the sample was filtered through a paper filter into a 100 ml measuring flask and brought to the mark with distilled water. The resulting solution was analyzed on an atomic absorption spectrometer with the burner tip rotated 30° relative to the light beam of a full cathode lamp along the analytical line at 285.2 nm. Ion concentrations were determined from the calibration graph of the dependence of luminescence intensity on the concentration of the target ion solution.

2.2.18. Determination of petroleum product content

Petroleum product content (mg/kg) was determined according to PND F 16.1:2.21-98 [40]. A cuvette with the sample was placed in the measuring chamber, and measurements were performed according to the operating documentation for a near-infrared spectrometer. Measurements were repeated with another sample taken from the same soil sample. The mass fraction of petroleum products in each measurement sample was calculated using the spectrometer software.

2.2.19. Determination of benz(a)pyrene content

Benz(a)pyrene content (mg/kg) was determined according to PND F 16.1:2:2:2.2:2.3:3.39-2003 [41]. For this purpose, 15 ml of methylene chloride was added to 1 g of soil placed in a conical flask. The flask was placed in a shaker for 30 minutes at 550 rpm. The extract was filtered through a paper filter into a test tube for evaporation. The extraction procedure was repeated, and the extracts were combined and evaporated to 1-2 ml. Next, 3-5 ml of hexane were added to the residue and evaporated again to a volume less than 0.5 ml. Hexane was added again to bring the volume up to 2 ml, and the mixture was transferred to an aluminum oxide column. It was washed with 20 ml of hexane, then eluted with 50 ml of a 10:90 mixture of methylene chloride and hexane. The eluate was evaporated to a dry state and then dissolved in 5 ml of acetonitrile. The samples were analyzed on a high-performance liquid chromatographer with fluorimetric detection. Chromatography parameters: eluent feed rate – 0.2 ml/min, mobile phase – acetonitrile/water mixture=80:20, injection volume – 10 µl, excitation wavelength – 292 nm, registration wavelength – 405 nm.

2.2.20. Determination of volatile phenol content

The content of volatile phenols (mg/kg) was determined according to PND F 16.1:2.3:3.44-05 [42]. To construct a calibration graph, samples for calibration were prepared with the mass concentrations of phenol of 0-0.80 mg/l. To each flask, 5 ml of buffer solution with a pH of 10.0 (50 g of ammonium chloride, 50 ml of water, 350 ml of ammonia solution), 3 ml of 2% 4-aminoantipyrine solution, and 1 ml of 20% ammonium persulfate solution were added. The solution was brought to 100 ml with water, and after 10 minutes, the optical density was measured at a wavelength of 510 nm.

To the analyzed sample, 300 ml of d. water, 5 ml of 10% copper sulfate solution, and 5 ml of 10% sulfuric acid solution were added and distilled. Next, 200 ml of the distillation was diluted with 250 ml of water, and then 5 ml of buffer solution, 3 ml of 2% 4-amino antipyrine solution, and 1 ml of 20% ammonium persulfate solution were added to 50 ml of the obtained mixture and brought to the mark with d. water. D. water was used as a control. In 10 minutes after the addition of all reagents, the optical density was measured relative to the control in a cuvette with an optical layer thickness of 50 mm at a wavelength of 510 nm. The concentration of phenols Xp (mg/kg) was found from the calibration graph and determined using the formula:

$$X_p = \frac{X_k \cdot 100 \cdot 250}{V_{np} \cdot m}$$

where X_p – phenol content found from the calibration graph, mg/l; *100* – the volume of the flask, ml; *250* – the distillate volume, ml; V_{np} – the volume of the sample taken for analysis, ml; m – the weight of the sample taken for analysis in terms of absolutely dry soil, g.

2.2.21. Determination of formaldehyde content

Formaldehyde content was determined according to PND F 16.1:2.3:3.45-05 [43]. For this purpose, 300 ml of d. water was added to the sample suspension, and distillation was carried out. The resulting distillation was brought to a volume of 250 ml with water. Then 0.5 ml of a 2% solution of the sodium salt of chromotropic acid and 5 ml of sulfuric acid were added to 5 ml of the distillate and mixed gently. The test tubes were placed in a boiling water bath for 10 minutes. Then the contents of the test tubes were cooled and diluted with water to 20 ml. The solution was stirred again and photometrically analyzed in cuvettes with an optical layer thickness of 50 mm at a wavelength of 570 nm. A blank experiment was set up, running through all the stages of the analysis. Freshly distilled d. water served as a comparison solution.

The mass concentration of formaldehyde in soil X (mg/kg) was calculated according to the formula:

$$X = \frac{(C - C_0) \cdot 1000}{m}$$

where *C* – formaldehyde content found from the calibration graph, mg; C_o – formaldehyde content in the blank experiment, mg; *m* – *the* weight of the sample taken for analysis in terms of absolutely dry soil, g; *1,000* – conversion factor per 1 kg of soil (waste).

2.2.22. Determination of pesticide content

The content of HCH and its isomers (α-HCH, β-HCH, γ-HCH) and DDT and its metabolites (4.4'-DDD, 4.4'-DDE, 4.4'-DDT) was determined according to GOST ISO 10382 [44]. For this purpose, 50 ml of acetone was added to 20 g of the sample placed in a conical flask, and extraction was carried out using a shaker for 15 minutes at 550 rpm. Then the extraction was repeated twice with 50 ml of petroleum ether. The extracts were collected in a 2-l separating funnel and the acetone was removed by shaking the mixture twice with 500 ml of water. The sample was filtered through anhydrous sodium sulfate into an evaporation flask and evaporated to a volume of 1 ml. The extract was purified on an aluminum oxide column, then transferred to the column and eluted with 20 ml petroleum ether. Next, it was divided into 2 parts. The first part was set aside, and the second part was concentrated by evaporation to a volume of 1 ml. To the obtained extract, 2 ml of tetrabutylammonium sulfite was added. Next, 10 ml of water was added, and the mixture was shaken for 1 minute. The organic phase was separated, and anhydrous sodium sulfate was added to remove moisture. Then gas chromatographic analysis with electron capture detection was carried out. Chromatography parameters: injector temperature – 210ºC, column temperature – 80ºC for 4 minutes, then heated at a rate of 4ºC/min up to 300ºC, carrier gas – helium, carrier gas flow velocity – 20-30 cm/s.

2.2.23. Data analysis

Data were subjected to analysis of variance (ANOVA) using Statistica 10.0 (StatSoft Inc., 2007, USA). Post hoc analysis (Duncan's test) was performed to identify samples that were significantly different from each other. The equality of variances of the extracted samples was tested using Levene's test. Differences between mean values were considered significant if the confidence interval was less than 5% ($p<0.05$).

2.2.24. Calculation of the amount of fertilizers

The factors considered when determining the fertilizer dose were the amount of nutrients in the samples, fertilizer properties, and application methods. Fertilizer doses are expressed as the amount of nutrients contained in the fertilizer. Thus, the doses of nitrogen fertilizers were expressed in kilograms of pure nitrogen, for phosphorus fertilizers phosphoric acid anhydride (P_2O_5) was taken as the active ingredient, and for potassium fertilizers – potassium oxide (K_2O). The doses of applied fertilizers by the amount of active ingredient were calculated according to the following formula:

$$X = \frac{a \cdot 100}{b}$$

where *X* – the weight of the fertilizer, kg, *a* – the recommended dose of active ingredient per ha, kg, and *b* – active ingredient content in the given fertilizer, kg.

2.2.25. Calculation of the amount of seeds

The sowing suitability of seeds was determined by the percentage of physically pure and germinable seeds and was calculated by the product of purity and germination divided by 100:

$$P = \frac{A \cdot B}{100}$$

where *P* – sowing suitability; *A* – physical purity; *B* – germination.

Recalculation of seeding rates to actual sowing suitability in single-species crops was performed using the formula:

$$H_1 = \frac{H \cdot 100}{p}$$

where *H* – the seeding rate at 100% sowing suitability; H_1 – the seeding rate adjusted for actual sowing suitability; *p* – sowing suitability of seeds.

The seeding rate for each species in the grass mixture was calculated according to the formula:

$$H_1 = \frac{Y \cdot H}{P}$$

where H_1 – the seeding rate (kg/ha) of the species included in the grass mixture; *H* – the seeding rate in pure form, kg/ha; *Y* – the species' inclusion in the grass mixture, %; *P* – sowing suitability of seeds, %.

3. Results and discussion

3.1. Results on agrophysical, agrochemical, and biochemical indicators

The content of petroleum products is not regulated by SanPiN 1.2.3685-21 [45] but is standardized by GOST 17.5.1.03-86 [46]. In Sample 1, petroleum products are under the threshold limiting value (TLV) (73.6 mg/kg) and background values (30 mg/kg), yet the levels in Sample 2 are more than 4 times higher (131 mg/kg). The content of ben(a)pyrene, volatile phenols, HCH and its isomers, and DDT and its metabolites in soil samples falls below TLV/approximate permissible concentration (APC) [45, 46] and background values (negative control).

Samples 2 are marked by alkaline values of pH (water) and pH (salt) indicators compared to negative control. The content of organic matter in terms of humus is 2 or more times lower in the studied samples compared to the background value (9.35%). The lowest amount of organic matter is noted in Sample 1 (0.8 %).

The gross content of copper, nickel, lead, cobalt, chromium, zinc, and manganese stays below TLV/APC levels. However, in all samples apart from Sample 2, this indicator is higher than the background level (16.9 mg/kg) by approximately 1.0. Arsenic levels above the TLV/APC are found in Sample 1 (5.3 mg/kg). Exceedance of the background level of nickel is observed in Sample 1 (28.0 mg/kg). Above-background lead content is demonstrated by

Samples 2 (22.4 mg/kg). Samples 1 and 2 exceed background cobalt levels by approximately 1-2 units on average. Chromium content higher than the background level is detected in Sample 1 (74 mg/kg). The content of manganese in Sample 2 (24.9 mg/kg) exceeds the background value by 1.5 times.

The content of copper does not exceed the TLV. However, all samples exceed the background value for mobile forms of zinc, manganese, copper, lead, nickel, chromium, and cobalt.

With the exception of petroleum products and arsenic content, soil samples from some territories demonstrate no exceedances of TLV/APC indicators by the studied parameters. This observation confirms that restoration activities have been conducted in the studied areas before. This also confirms the accumulation of various forms of nitrogen in the soils, which can be transformed by microorganisms. However, the activity of these microorganisms is extremely limited in the disturbed territories of coal-mining enterprises. The accumulation of nitrogen in the disturbed areas of coal mining enterprises occurs, among other things, due to the oxidation of coal or coal dust over time with the involvement of certain microorganisms in these areas. Ammonium/nitrate nitrogen content indicates that the soils of all the studied territories are virtually not cultivated and have been undisturbed for some time. An exception is the coal mine 2, samples from which contain more than 30 mg/kg of nitrate nitrogen that can later be used by plants for growth.

The content of mobile phosphorus in the considered soil samples ranges from 14 to 52 mg/kg. Most areas show levels higher than negative control. However, most often, phosphorus is found in the soils of disturbed areas in a form that makes it inaccessible to plants, so it is not consumed and accumulates in the soil layers, causing pollution.

Hydrolytic acidity (mmol/100 g) and the sum of consumed bases (mmol/100 g) are used to establish soil saturation, which indicates the need for soil liming. A value under 50% suggests a strong need for liming, 50-70% – average necessity, 70-80% – a low need, and a level higher than 80% shows that the soil does not require liming. The level of saturation of soil samples from the studied areas exceeds 90%, suggesting that there is no need for preliminary liming (before planting). In terms of all the other macro- and micro-elements needed by plants, all soil samples, including negative control, show low levels. This points to the need to introduce mineral and organic fertilizers and to increase organic matter (humus) content in the soil layers of technologically disturbed areas as part of phytoremediation measures. Low quantities (<0.015%) of magnesium ions, calcium ions, sodium ions, chloride ions, sulfate ions, carbonate ions, and bicarbonate ions (%, water extract) indicate the low salinity of soils in the studied areas.

The results of determining the granulometric (grain) composition and type (according to Kachinsky) of soil samples are presented in Tables 1 and 2, respectively.

Depending on the degree of contamination and other characteristics, soils are divided according to their suitability for biological reclamation: suitable, marginally suitable, and unsuitable. Non-saline loams and heavy and medium loams among others, belong to potentially fertile soils, the low natural fertility of which is due to the lack of nutrients, especially nitrogen and phosphorus [12, 46]. Therefore, the soil of all studied territories can be used for bioremediation.

Prior to the initial stage of recultivation, soil samples from the coal mine 1 with the norms and requirements of the authorization documentation (GOST, SanPiN 1.2.3685-21) by the content of carbonate ion, bicarbonate ion, copper, lead, zinc, cadmium, and petroleum products. The analyzed samples of soils from the coal mine 1 are rich in nickel (44.3±13.1 mg/kg). The total contamination index (Z_c) of the soils and subsoils of the sites are categorized as acceptable according to SanPiN 2.1.7.1287-03; therefore, their use is possible without restrictions. According to the empirical data, the content of petroleum products, regulated by GOST 17.5.1.03-86, is under the TLV (73.6 mg/kg) and background values (30 mg/kg) in three territories, while petroleum product content in the remaining sample (the coal mine 2) exceeds the background level by almost four times (131 mg/kg). The content of benz(a)pyrene, volatile phenols, HCH and its isomers, and DDT and its metabolites in the soil samples of all investigated territories does not exceed TLV/APC and background values (negative control). Soil samples from the coal mine 2 demonstrate alkaline values of pH (water) and pH (salt) in comparison with negative control. The content of organic matter in terms of humus is 2 or more times lower in the studied samples compared to the background value (9.35%). The lowest amount of organic matter is observed in samples from the coal mine 1 (0.8%).

The gross content of copper, nickel, lead, cobalt, chromium, zinc, and manganese does not exceed the TLV/APC values. However, for all samples, except for the territory of the coal mine 2, the value of these indicators exceeds the background value (16.9 mg/kg) by about 1.0. The nickel content is above the background level in the samples from the coal mine 1 (28.0 mg/kg). Lead levels exceed the background value in the coal mine 2 (22.4 mg/kg). For cobalt, exceedance of the background indicator by 1-2 units on average is noted in samples from three out of four territories. The chromium content is above the background value in the coal mine 1 (74 mg/kg). The coal mine 2 (24.9 mg/kg) exceeds the background value by 1.5 times, respectively. The copper content does not surpass the TLV level. All samples are over the background levels of mobile forms of zinc, manganese, copper, lead, nickel, chromium, and cobalt.

3.2. Development of the scheme of recultivation

3.2.1. The coal mine 1

The objects of recultivation of Osinnikovskoye Pole under the project include internal and external dumps, technogenic surface outside the dumps, roads, water disposal facilities, corridors under power lines, backfilling the traces of oriented hydrofracturing (residual quarry pit, cavities, cracks). The biological recultivation stage involves work on planting trees and sowing perennial grasses. Project solutions for carrying out the biological recultivation stage are presented in Table 3. For the forestry direction of reclamation, the total requirement for seeds of perennial grasses at the 1st stage of recultivation (2020-2031) is estimated to be 3,960 kg. The total need for woody and shrubby plants at the 1st stage of recultivation (2020-2031) is 501,165 pcs.

Table 1. Content of fractions (%) in soil samples (areometric method)

Sample	Soil fractions, mm										
	<0.002	0.01-0.002	0.01-0.05	0.05-0.1	0.10-0.25	0.25-0.50	0.5-1	1-2	2-5	5-10	>10
1 The coal mine 1	22.33	29.41	33.22	6.01	4.43	2.27	0.77	0.24	0.46	0.20	0.67
2 The coal mine 2	16.48	13.67	20.50	6.34	6.69	4.87	4.24	6.05	9.31	4.76	7.09
3 Negative control (background)	17.30	24.56	41.87	3.50	3.69	2.61	2.01	1.59	2.11	0.47	0.29

Table 2. Content of fractions (%) in soil samples (areometric method)

Sample	Soil fractions, mm							Phys. sand/Phys.clay	Soil type*
	<0.002	0.01-0.002	0.01-0.05	0.05-0.1	0.10-0.25	0.25-0.50	0.5-1		
1 The coal mine 1	22.68	29.88	33.75	6.11	4.50	2.30	0.78	47.44/52.56	Heavy loamy
2 The coal mine 2	22.64	18.78	28.16	8.71	9.19	6.70	5.82	58.58/41.42	Medium loamy
3 Negative control (background)	18.11	25.71	43.82	3.67	3.86	2.73	2.10	56.18/43.82	Medium loamy

*by mechanical composition

Table 3 Project solutions for the biological stage of recultivation (the coal mine 1)

Indicator	Unit of measure	Indicator content
1st stage of recultivation		
Land subject to recultivation	ha	120
Type of biological recultivation	ha	Forestry direction
2nd stage of recultivation		
Land subject to recultivation	ha	1,508.2899
Type of biological recultivation	ha	Forestry direction – 1,501.973
		Agricultural direction – 6.3169

Table 4. Requirement for woody plants and shrubs at the 1st stage of biological recultivation (the coal mine 1, 2021-2032, excluding the maintenance of plantings and crops)

Culture	Area, ha	Number of plants per ha, pcs/ha	Seedling requirement, pcs
surface			
Pine	70.55	4,000	282,200
Rowan	70.55	300	21,165
IN TOTAL			30,335
slopes			
Rowan	49.45	400	197,800
IN TOTAL			197,800
SUM TOTAL			501,165

Table 5. Requirement for woody plants and shrubs at the 2nd stage of recultivation (the coal mine 1, after 2031)

Culture	Area, ha	Number of cultures per ha, pcs/ha	Seedling requirement, pcs
surface			
Pine	1,178.403	4,000	4,713,612
Rowan	1,178.403	300	353,521
IN TOTAL			5,067,133
slopes			
Rowan	323.57	400	1,294,280
IN TOTAL			1,294,280
SUM TOTAL			6,361,413

Table 6. Total seed requirement for perennial grasses at the 1st stage of biological recultivation (the coal mine 1, 2021-2032, excluding the maintenance of plantings and crops)

Culture	Area, ha	Grass seeding rate, kg/ha	Seed requirement, kg
Timothy	120	6	720
Meadow fescue	120	12	1,440
Red clover	120	15	1,800
IN TOTAL			3,960

Table 7. Total seed requirement for perennial grasses at the 2nd stage of recultivation (the coal mine 1, after 2031)

Culture	Area, ha	Grass seeding rate, kg/ha	Seed requirement, kg
Timothy	1,501.973	6	9,012
Meadow fescue	1,501.973	12	18,024
Red clover	1,501.973	15	22,530
IN TOTAL			49,565

Table 8. Fertilizer application rates at the 1st stage of biological recultivation (the coal mine 1, 2021-2032)

Mineral fertilizers	Number of ha	Mineral fertilizer application rate, kg (primary pre-sowing)	
		Application rate, kg per ha	Application rate
Nitrogen (urea)	120	130	15,600
Phosphorus (double superphosphate)	120	95	11,400
Potassium (potassium chloride)	120	67	8,040
IN TOTAL			35,040

Table 9. Fertilizer application rates at the 2nd stage of recultivation (the coal mine 1, after 2031)

Mineral fertilizers	Number of ha	Mineral fertilizer application rate, kg (primary pre-sowing)	
		Application rate, kg per ha	Application rate
Nitrogen (urea)	1,501.973	130	195,257
Phosphorus (double superphosphate)	1,501.973	95	142,687
Potassium (potassium chloride)	1,501.973	67	100,632
IN TOTAL			438,576

Table 10. Seed requirement for perennial grasses (the coal mine 1)

Culture	Area, ha	Seeding rate, kg/ha	Seed requirement, kg
alfalfa	6.3169	14	88
meadow fescue	6.3169	20	126
smooth brome	6.3169	18	114
IN TOTAL			328

Table 11. Fertilizer application rates during reclamation (the coal mine 1)

Mineral fertilizers	Number of ha	Mineral fertilizer application rate, kg (primary pre-sowing)	
		Application rate, kg per ha	Application rate
Nitrogen (urea)	6.3169	130	821.2
Phosphorus (double superphosphate)	6.3169	95	600.1
Potassium (potassium chloride)	6.3169	67	423.2
IN TOTAL			1,844.5

Table 12. Scope of work in the forestry direction (the coal mine 2)

Name of work	Unit of measure	Quantity per ha	Area, ha	Quantity
1. Soil loosening before and after planting	ha	2	322.3	644.6
2. Planting grasses	ha	1	322.3	322.3
Seeds of perennial grasses:	kg	25	322.3	8,058
Melilot	kg	11	322.3	3,545
Meadow fescue	kg	7	322.3	2,256
Slender wheatgrass	kg	7	322.3	2,256
3. Marking the area	ha	1	322.3	322.3
4. Burying and preparing seedlings for planting with a 20% excess	pcs.	4,800	322.3	1,547,040
5. Planting the seedlings	pcs.	4,800	322.3	1,547,040
6. Planting the material (with a 20% excess)	pcs.	4,800	322.3	1,547,040
Pine	pcs.	1,920	322.3	618,816
Birch	pcs.	960	322.3	309,408
Sea buckthorn	pcs.	960	322.3	309,408
Silverberry and caragana	pcs.	960	322.3	309,408

Table 13. Scope of work in the agricultural direction (the coal mine 2)

Name of work	Unit of measure	Quantity per ha	Area, ha	Quantity
1. Soil discing	ha	1	700.2	700.2
2. Mechanized application of mineral fertilizers	ha	1	700.2	700.2
Fertilizers:				
Ammonium nitrate	q	1.3	700.2	910.3
Granulated superphosphate	q	1.8	700.2	1,260.4
Potassium chloride	q	2.0	700.2	1,400.4
3. Double rolling of soils, before and after sowing, with crosskill rollers	ha	2	700.2	1,400.4
4. Grass sowing	ha	1	700.2	700.2
Seeds of perennial grasses:	kg	25	700.2	17,505
Melilot	kg	11	700.2	7,702
Meadow fescue	kg	7	700.2	4,091.5
Slender wheatgrass	kg	7	700.2	4,091.5
5. Grass cutting in July-August of the 2nd and 3rd year	ha	2	700.2	1,400.4

The total requirement for woody plants and shrubs at the 2nd stage of recultivation (after 2031) amounts to 6,361,413 pcs. The total requirement for perennial grass seeds at the 2nd stage of recultivation (after 2031) is 49,565 kg. The requirement for woody plants and shrubs at the 1st recultivation stage (2020-2031) is given in Table 4. The requirement for woody plants and shrubs at the 2nd stage of recultivation (after 2031) is provided in Table 5.

Calculations of seed requirements for grasses at the 1st stage of recultivation (2020-2031) are given in Table 6. Calculations for grasses at the 2nd stage of recultivation (after 2031) are provided in Table 7.

The seeds to be sown in the planned areas should be of varieties included in the State Register of Breeding Achievements approved in accordance with the established procedure [47]. It is forbidden to use seeds that have been found to contain:

− weeds (seeds, fruits), pests, and pathogens of quarantine importance for Russia, according to the list approved in the established order;

− live pests and their larvae damaging the seeds of the respective crop, except for mites, the presence of which is allowed in reproductive seeds for commercial purposes in the amount not exceeding 20 pcs/kg;

− seeds of the poisonous plants *Heliotropium dasyocarpum Ldb.* and *Trichodesma incanum D.C.*

To ensure the effective use of mineral nutrition elements by plants, the project recommends the application of mineral fertilizers. The amount of fertilizers to be applied at the 1st stage of recultivation is 3,500 kg and at the 2nd stage – 438,576 kg.

Calculations of mineral fertilizer rates at the 1st and 2nd stages of recultivation are given in Tables 8 and 9.

For the agricultural direction of recultivation, the recommended perennial grasses to be sown are either zonal herbaceous vegetation species or a ready-made grass mixture. The seed sowing depth is 2-3 cm. The grass mixture of cereal-legume grasses used for sowing perennial grasses contains alfalfa, meadow fescue, and smooth brome.

The seeds sown in the planned areas are of the varieties included in the State Register of Breeding Achievements approved in accordance with the established procedure [47].

The total seed requirement for perennial grasses at the biological stage of agricultural recultivation, Stage 2, is estimated to be 328 kg (Table 10). The total amount of mineral fertilizers applied to the recultivated areas during the 2nd stage of recultivation totals 1,844.5 kg (Table 11).

3.2.2. The coal mine 2

The technical stage of recultivation (area of the technical recultivation stage – 322.3 ha) is planned to be carried out. This includes preparation of the territory, surface planning, flattening of slopes, backfilling of negative relief forms, and creation of a recultivation layer. The biological stage (area of the biological stage – 322.3 ha) is also planned to be carried out, including agricultural and phytomeliorative measures. To combat soil erosion, the following measures are envisaged:

− planning of horizontal surfaces with a 1-3° slope to one side or from the middle to the edges; no drainless depressions should be left on the surface;

− terracing, flattening of dump slopes to 20°;

− sowing grasses and planting woody plants and shrubs along the slopes by horizons;

− sowing of grasses within two weeks after the application of the fertile soil layer.

In the forestry direction of reclamation, the following operations are required:

− soil loosening before and after planting;

− sowing of grasses – manually;

− planting woody and shrub plantations – manually.

The scope of works in the forestry and agricultural directions of recultivation is described in Tables 12 and 13.

4. Conclusions

The research was conducted to study the agrophysical, agrochemical, and biological indicators of soils of two Kuzbass coal dumps, the coal mine 1 and the coal mine 2, after post-mining recultivation. Analysis of coal mine soil samples proves the studied territories suitable for the biological recultivation stage despite exceedances of several pollution indicators (arsenic, cadmium, nickel, cobalt, chromium, manganese). A list of woody, shrub, and herbaceous plants with advantages for use in the given region (frost tolerance, salinity tolerance, and low soil requirements) is compiled for the purposes of intensive ameliorative impact with the cultivation of annual and perennial cereal and leguminous crops for the restoration and formation of the root-bearing layer and its enrichment with organic matter. The rates of potassium, phosphorus, and nitrogen fertilizer application are calculated considering the obtained data on the content of minerals and organic compounds in the studied soil.

5. Funding

This research was funded by the Russian Science Foundation and the Ministry of Science, Higher Education and Youth Policy of Kuzbass, grant number 22-14-20011.

References

[1] S. Aipeisova, N. Utarbayeva, A. Maui, E. Kazkeev, & A. Baubekova. (2022). Fabaceae Lindl. Species in the floristic composition of the Aktobe Floristic District. International Journal of Environmental Studies. 80(4): 1076-1087. https://doi.org/10.1080/00207233.2022.2136851

[2] R. Yerezhepkyzy, A. Karatayeva, G. A. Kuanalieva, B. M. Konysbai, & D. A. Azhinurina. (2017). Legal regulation of public access to information in the field of environmental protection and use of natural resources. Journal of Legal, Ethical and Regulatory Issues. 20(2): 1-6.

[3] B. Koſodziej, M. Bryk, A. Sſowiſska-Jurkiewicz, K. Otremba, & M. Gilewska. (2016). Soil physical properties of agriculturally reclaimed area after lignite mine: A case study from central Poland. Soil and Tillage Research. 163: 54-63. https://doi.org/10.1016/j.still.2016.05.001

[4] A. V. Martirosyan, Y. V. Ilyushin, & O. V. Afanaseva. (2022). Development of a distributed mathematical model and control system for reducing pollution risk in mineral water aquifer

systems. Water. 14(2): 151. https://doi.org/10.3390/w14020151

[5] Y. Ilyushin, & O. Afanaseva. (2020). Modeling of a spatial distributed management system of a preliminary hydro-cleaning gasoline steam column, in International Multidisciplinary Scientific GeoConference SGEM 2020, vol. 2.1. STEF92 Technology, Sofia, Bulgaria. 531-538. https://doi.org/10.5593/sgem2020/2.1/s08.068

[6] S. Quegan, C. Beer, A. Shvidenko, I. A. N. McCallum, I. C. Handoh, P. Peylin, & C. Schmullius. (2011). Estimating the carbon balance of central Siberia using a landscape-ecosystem approach, atmospheric inversion and Dynamic Global Vegetation Models. Global Change Biology. 17(1): 351-365. http://dx.doi.org/10.1111/j.1365-2486.2010.02275.x

[7] A. Kuderina, I. Kuderin, D. Bekezhanov, B. Aitimov, D. Nurbek, & I. Amreeva. (2021). Environmental and legal regulation of the handling of chemicals. Journal of Environmental Management and Tourism. 12(2): 371-381. https://doi.org/10.14505//jemt.v12.2(50).06

[8] B. Nasiyev, T. Vassilina, A. Zhylkybay, V. Shibaikin, & A. Salykova. (2021). Physicochemical and biological indicators of soils in an organic farming system. Scientific World Journal. 2021(4): 9970957. https://doi.org/10.1155/2021/9970957

[9] B. Yessimbek, B. Mambetov, R. Akhmetov, D. Dosmanbetov, K. Abayeva, A. Kozhabekova, A. Oraikhanova, & M. Baibatshanov. (2022). Prevention of desertification and land degradation using Black Saxaul in arid conditions. OnLine Journal of Biological Sciences. 22(4): 484-491. https://doi.org/10.3844/ojbsci.2022.484.491

[10] M. Ongayev, S. Denizbayev, G. Ozhanov, B. Yesmagulova, N. Umbetkaliyev, & T. Shadyarov. (2023). Analysis of hydrochemical parameters of surface water sources used for watering pastures to improve the water quality. Caspian Journal of Environmental Sciences. 21(4): 875-883.

[11] Z. Dukenov, A. Utebekova, A. Kopabayeva, M. Shynybekov, R. Akhmetov, Z. Rakymbekov, A. Bekturganov, & D. Dosmanbetov. (2023). Influence of climatic changes on the dendrochronological features of Tugai forests along the Syr Darya and Ili Rivers in the Territory of Kazakhstan. International Journal of Design & Nature and Ecodynamics. 18(4): 975-982. http://dx.doi.org/10.18280/ijdne.180425

[12] T. S. Chibrik. (2002). Osnovy biologicheskoi rekultivatsii [Fundamentals of biological remediation]. Ural University Publishing House, Ekaterinburg, Russia. 172 p.

[13] P. Kalashnikov, A. Kulanov, E. Nesipbekov, A. Kaishatayeva, & S. Kantarbayeva. (2023). Impact of state and legal regulation on the sustainable development of agricultural territories and Improving the standard of living of the population. Journal of Environmental Management and Tourism. 14(1): 82-88. http://dx.doi.org/10.14505/jemt.v14.1(65).08

[14] O. Belousova, T. Medvedeva, & Z. Aksenova. (2021). A botanical gardening facility as a method of reclamation and integration of devastated territories (based on the example of the Eden Project). Civil Engineering and Architecture. 9(5): 1309-1317. http://dx.doi.org/10.13189/cea.2021.090504

[15] A. Bugubaeva, A. Kuprijanov, V. Chashkov, S. Kuanyshbaev, K. Valiev, S. Mamikhin, A. Shcheglov, A. Nugmanov, A. Bulaev, G. Sultangazina, K. Kunanbayev, O. Chernyavskaya, G. Baubekova, G. Ruchkina, O. Safronova, M. Uxikbayeva, & Y. Sokharev. (2023). Productivity assessment of various plant communities at uranium mine sites in Central Kazakhstan. SABRAO Journal of Breeding and Genetics. 55(3): 864-876. http://doi.org/10.54910/sabrao2023.55.3.21

[16] D. Makhmetova, E. Tlessova, M. Nurkenova, A. Auelbekova, & B. Issayeva. (2023). Waste management strategy of agricultural enterprises to improve the efficiency of rural development. Journal of Environmental Management and Tourism. 14(3): 623-631. http://doi.org/10.14505/jemt.v14.3(67).02

[17] A. Shaimerdenova, L. G. Agapitova, A. V. Bobrova, Y. Akhmetov, V. A. Sinyukov, P. N. Sharonin, A. G. Dobrovolsky, D. I. Ryakhovsky, E. E. Krasnovskiy, & A. D. Ten. (2023). Development of optimal crop production model considering existing natural-climatic risks increasing crop yields. SABRAO Journal of Breeding and Genetics. 55(3): 778-795. http://doi.org/10.54910/sabrao2023.55.3.15

[18] L. Khoruzhy, Y. Katkov, E. Katkova, A. Romanova, & M. Dzhikiya. (2023). Sustainable development of agricultural enterprises with an active environmental stance: Analysis of inter-organizational management accounting. Journal of Law and Sustainable Development. 11(3): e386. https://doi.org/10.55908/sdgs.v11i3.386

[19] Iu. A. Kurilo, E. V. Donets, & A. I. Grigorev. (2020). Opyt po issledovaniiu prodolzhitelnosti vliianiia neftianogo zagriazneniia na kharakteristiku bioelektricheskogo soprotivleniia berezy povisloi (Betula pendula Roth.) [Experience in the study of the duration of the influence of oil pollution on the characteristic of bioelectrical resistance of birch (Betula pendula Roth.)]. Bulletin of Nizhnevartovsk State University. 1: 68-74. https://doi.org/10.36906/2311-4444/20-1/11

[20] Rosstandart. (2018). GOST 17.4.4.02–2017 Nature protection. Soils. Methods for sampling and preparation of soil for chemical, bacteriological, helmintological analysis. Standartinform, Moscow, Russia.

[21] P. Conte, A. Agretto, R. Spaccini, & A. Piccolo. (2005). Soil remediation: Humic acids as natural surfactants in the washings of highly contaminated soils. Environmental Pollution. 135(3): 515-522. https://doi.org/10.1016/j.envpol.2004.10.006

[22] T. A. Petrova, & E. Rudzish. (2021). Rekultivatsiia tekhnogenno-narushennykh zemel s primeneniem

osadkov stochnykh vod v kachestve meliorantov [Utilization of sewage sludge as an ameliorant for reclamation of technogenically disturbed lands]. Journal of Mining Institute. 251(5): 767-776. https://doi.org/10.31897/PMI.2021.5.16

[23] Rosstandart. (2020). GOST R 59070-2020. National standard of the Russian Federation. Environmental protection. Reclamation of disturbed and oil-contaminated lands. Standartinform, Moscow, Russia.

[24] Rosstandart. (2019). GOST R 58596. National standard of the Russian Federation. Soils. Methods for determination of total nitrogen. Standartinform, Moscow, Russia.

[25] Rosprirodnadzor. (2002). PND F 16.2.2:2.3:3.30-02. Quantitative chemical analysis of soil. Methods for measuring ammonium nitrogen in solid and liquid production and consumption waste, sediments, sludge, activated sludge, bottom sediments by the photometric method. Moscow, Russia.

[26] Rosprirodnadzor. (2010). PND F 16.1:2:2.2:3.67-10. Quantitative chemical analysis of soil. Methods of measuring the mass fraction of nitrate nitrogen in samples of soil, soil, sediment, silt, production and consumption waste by the photometric method with salicylic acid. Federal Service for Environmental, Technological and Nuclear Supervision, Moscow, Russia.

[27] State Standard of the USSR. (1992). GOST 26213-91. Soils. Methods for determination of organic matter. Izdatel'stvo standartov, Moscow, USSR.

[28] Rosprirodnadzor. (2008). PND F 16.1:2.2:2.3:3.58-08. Quantitative chemical analysis of soil. Methodology for measuring the mass fraction of moisture in solid and liquid waste of production and consumption, soils, sediments, sludge, active sludge of treatment facilities, bottom deposits by gravimetric method. Federal Service for Supervision of Natural Resources, Moscow, Russia.

[29] Rosstandart. (2020). GOST R 53380-2009. National standard of the Russian Federation. Soils and Grounds. Hothouse grounds. Specifications. Standartinform, Moscow, Russia.

[30] Rosstandart. (2021). GOST R 59540-2021. Soils. Methods for laboratory determination of the degree of salinity. Standartinform, Moscow, Russia.

[31] State Standard of the USSR. (1988). GOST 27784-88. Soils. Method for determination of ash content in peat and peat-containing soil horizons. Izdatel'stvo standartov, Moscow, USSR.

[32] State Standard of the USSR. (2006). GOST 28268-89. Interstate standard. Soils. Methods of determination of moisture, maximum hygroscopic moisture and moisture of steady plant fading. Standartinform, Moscow, Russia.

[33] State Standard of the USSR. (1985). GOST 26483. State Standard of the USSR. Soils. Preparations of salt extract and determination of its pH by CINAO method. Izdatel'stvo standartov, Moscow, USSR.

[34] Rosprirodnadzor. (2002). PND F 16.2.2:2.3:3.31-02. Quantitative chemical analysis of soil. Methods for measuring alkalinity in solid and liquid wastes of production and consumption, sediments, sludge, activated sludge, bottom sediments by potentiometric titration. Moscow, Russia.

[35] State Standard of the USSR. (1992). GOST 26212. International standard. Soils. Determination of hydrolytic acidity by Kappen method modified by CINAO. Izdatel'stvo standartov, Moscow, USSR.

[36] State Standard of the USSR. (2011). GOST 26423-85. Interstate standard. Soils. Methods for determination of specific electric conductivity, pH and solid residue of water extract. Standartinform, Moscow, Russia.

[37] FR.1.31.2020.38220. Methodology for measuring the content of exchangeable sodium, cation exchange capacity in solid objects with subsequent calculation of the degree of solonetzicity.

[38] State Standard of the USSR. (1988). GOST 27821-88 Soils. Determination of base absorption sum by Kappen method. Izdatel'stvo standartov, Moscow, USSR.

[39] FR.1.31.2021.38757. Methodology for measuring the mass fraction of dry residue, carbonate ions, bicarbonate ions (total alkalinity), chloride ions, sulfate ions, potassium, calcium, magnesium, and sodium ions in the filtrate of water extract from solid objects with subsequent calculation of the sum of toxic salts.

[40] Rosprirodnadzor. (1998). PND F 16.1:2.21-98 Quantitative chemical analysis of soil. Methods for measuring the mass fraction of oil products in soil and soil samples by the fluorimetric method. Moscow, Russia.

[41] Federal Service for Environmental, Technological and Nuclear Supervision. (2003). PND F 16.1:2:2.2:2.3:3.39-2003. Quantitative chemical analysis of soils. Method of measuring the mass fraction of benz(a)pyrene in soil samples, soils, solid waste, bottom sediments, sewage sludge by high-performance liquid chromatography with fluorescent detection. Ministry of Natural Resources of the Russian Federation, Moscow, Russia.

[42] Federal Service for Environmental, Technological and Nuclear Supervision. (2005). PND F 16.1:2.3:3.44-05. Quantitative chemical analysis of soil. Methods for measuring the mass fraction of volatile phenols in soil samples, sewage sludge and waste by the photometric method after steam stripping. Moscow, Russia.

[43] Federal Service for Environmental, Technological and Nuclear Supervision. (2005). PND F 16.1:2.3:3.45-05. Quantitative chemical analysis of soil. Methods for measuring the mass fraction of formaldehyde in soil samples, sewage sludge and waste by the photometric method with chromotropic acid. Moscow, Russia.

[44] Rosstandart. (2020). GOST ISO 10382-2020. International standard. Soil quality. Determination of organochlorine pesticides and polychlorinated biphenyls. Gas-chromatographic method with electron capture detection. Standartinform, Moscow, Russia.

[45] Chief State Sanitary Doctor of the Russian Federation. (2021). SanPiN 1.2. 3685-21 Hygienic standards and requirements for ensuring the safety and/or harmlessness of environmental factors for humans. http://publication.pravo.gov.ru/Document/View/0001202102030022?ysclid=lot55iiboh165395303

[46] State Standard of the USSR. (2002). GOST 17.5.1.03-86. International standard. Nature protection. Lands. Classification of overburden and enclosing rocks for biological recultivation of lands. IPK Izdatel'stvo standartov, Moscow, Russia.

[47] Rosstandart. (2005). GOST R 52325-2005 National standard of the Russian Federation. Seeds of agricultural plants. Varietal and sowing characteristics. General specifications. Standartinform, Moscow, Russia.