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Development of technosol substrates based on mining waste and sewage sludge

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Abstract

The article focuses on developing an effective method for reclaiming anthropogenically disturbed areas through optimization of the composition of technosol substrates that incorporate industrial mineral waste and sewage sludge. The relevance of the study stems from the need to eliminate the negative consequences of mineral extraction and processing, which lead to the formation of vast tailings storage areas that adversely affect the environmental situation in the region. We investigated the physicochemical properties of dressing tailings and the differences in their properties upon addition of sewage sludge from three mining enterprises in the Murmansk Region: the loparite tailings storage facilities Karnasurt-1 and Umbozero (Revda settlement), and the apatite-nepheline tailings storage facility ANOF-3 (Kirovsk). Under laboratory conditions, we determined the component proportions in the technosol substrate, providing a reduction of pH to neutral values, an increase in the moisture-holding capacity of the substrates, and an improvement in the availability of essential plant nutrients. Phytotoxicity test confirmed the high biological activity of the formulated soil substrates and the positive effect of the introduced additive on the development of the test crops: radish (*Raphanus sativus* L.) and perennial ryegrass (*Lolium perenne* L.). The study identified the optimal balance between mineral tailings and sewage sludge, ensuring the best plant adaptation and the maximum reclamation efficiency for disturbed areas. The results obtained hold significant practical importance for land reclamation in areas with high load from the mining industry, contributing to the minimization of environmental risks, substrate stabilization, the formation of a sustainable vegetation cover, and the sustainable use of industrial and municipal waste. We noted the need to confirm the effectiveness of the proposed approach under long-term experimental conditions. The practical implementation of this technology will ensure environmentally sustainable economic activities in regions with intensive exploitation of raw material reserves, including the northern regions of Russia.

Keywords

reclamation; technosols; mining waste; sewage sludge; tailings storage facilities

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Introduction

Waste generated during mineral extraction and processing – dressing tailings, anthropogenic sands, and others – occupies significant areas and represents one of the most crucial factors of anthropogenic impact on the environment [1-3]. These anthropogenic formations create artificial

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geosystems characterized by disruption of natural topography, hydrological regime, and soil-vegetation cover [4].

Due to the absence of vegetation and low organic matter content, such areas undergo intensive wind and water erosion processes, as well as dust formation [5-7], which leads to deterioration of sanitary-hygienic conditions of the environment and poses a potential threat to human health [8-10]. The magnitude and nature of the negative impact of dust emissions on the human body largely depend on particle dispersity: PM_{10} particles (PM – from particulate matter) – dust particles less than 10 μm and 2.5 μm ($PM_{2.5}$). PM_{10} associate with respiratory system lesions, including chronic obstructive pulmonary disease [11], whereas $PM_{2.5}$ associate with anemia [12]. $PM_{2.5}$-PM_{10} particles can cause immunotoxic, cytotoxic, and potentially mutagenic effects; they are also linked to an increased risk of cardiovascular diseases, asthma, arterial hypertension, and stroke [13]. In addition, tailings storage facilities and dumps often serve as sources of secondary contamination of the aquatic environment due to migration of heavy metals, acid drainage, and toxic compounds [7, 14, 15], which can also exert a negative impact on human health and environmental state.

A distinctive feature of tailings storage facilities is their extremely low potential for natural recovery [16, 17]. Over decades, a stable vegetation cover cannot form on their surface due to the low fertility level, weak water-holding capacity, and deficiency of microelement composition in technosols [18-20]. The combination of these factors leads to prolonged environmental instability of disturbed areas and intensification of degradation processes. For the northern areas of Russia, the main provisions in the field of land reclamation are largely inapplicable, where the technical stage typically includes removal, storage, and subsequent use of the fertile soil layer [21]. Under subarctic and arctic conditions with extremely slow soil formation, performing such actions is practically impossible. In this regard, there arises a need for specialized reclamation measures aimed at accelerated formation of vegetation cover, substrate stabilization, and restoration of environmental functions of anthropogenically disturbed lands.

One of the promising directions of reclamation involves the use of by-products from industrial and municipal enterprises – in particular, sewage sludge (SS) [22, 23], which has fertilizing value, high water-holding capacity, content of useful macro- and microelements for plants, as well as a large amount of organic matter [24-26]. In terms of type, chemical composition, and physicochemical properties, SS can vary significantly depending on the wastewater type, water treatment system, and processing methods. The averaged composition of the sludge represents approximately 25-80 % organic matter, 5-20 % nitrogen, 2-20 % phosphorus, a set of nutrient elements necessary for plants – K, Ca, Mg, Na, as well as heavy metals Zn, Cu, Cr, Pb, Ni [27]. The use of SS in technosol substrates allows not only to accelerate the soil formation and ecosystem restoration, but also to solve the issues of resource conservation and waste utilization.

In Russian regulatory practice, some of the key documents governing the conditions for preparation, dewatering, and assessment of the suitability of mud and other sewage sludge for reclamation purposes include GOST R 54534-2011 “Resource Saving. Sewage Sludge. Requirements for Use in Reclamation of Disturbed Lands” and GOST R 59748-2021 “Technical Principles of Sewage Sludge Treatment. General Requirements”. Compliance with the provisions of these regulatory documents allows effective use of SS in reclamation works. At the same time, analysis of patent literature indicates that the development of technosol substrates involves a number of limitations related to the complexity of the component composition and significant engineering costs. Known solutions presented in patents RU 2497784 [28] and RU 2490240 [29] rely on multi-component formulations using sludge sediments, peat, and anthropogenic sandy materials, and involve lengthy preparation stages,

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including fermentation. The main disadvantages of these approaches include high engineering complexity and limited versatility of application.

The aim of this study is to develop technosol substrates based on local mining waste and SS, characterized by a neutral reaction of the medium, enhanced water-holding capacity and content of plant nutrient elements, which ensure sustainable formation of vegetation cover and minimize the negative environmental impact of accumulated waste from mining enterprises in the Murmansk Region.

Methods

Description of the study area. The Murmansk Region lies in the northwest of the European part of Russia, on the Kola Peninsula, and borders Karelia, Finland, and Norway. It sits almost entirely north of the Arctic Circle and is washed by the Barents and White seas. The climate is subarctic (Dfc according to Köppen – Geiger), maritime, moderated by the influence of the Gulf Stream. The topography represents tundra and taiga. Average January temperatures range from –8 to –15 °C, and July temperatures – from +8 to +15 °C.

Despite its small area (0.85 % of Russia), the region holds strategic importance and is noted for a prominent level of industrial development. The Kola Peninsula hosts about 60 large deposits, including copper-nickel, apatite-nepheline, iron, and rare-earth ores. The region provides 100 % of Russian production of apatite, nepheline, and baddeleyite concentrates, about 10 % of iron ore, and 7 % of refined copper. The concentration of mining and metallurgical enterprises creates a significant anthropogenic load on the environment [30].

Description of the materials studied. The study uses waste from tailings storage facilities of the Murmansk Region: dressing tailings of loparite ores from the Karnasurt-1 (LT1) and Umbozero (LT2) tailings storage facilities (Revda settlement), dressing tailings of apatite-nepheline ores from the ANOF-3 (ANT) tailings storage facility (Kirovsk) (Fig.1).

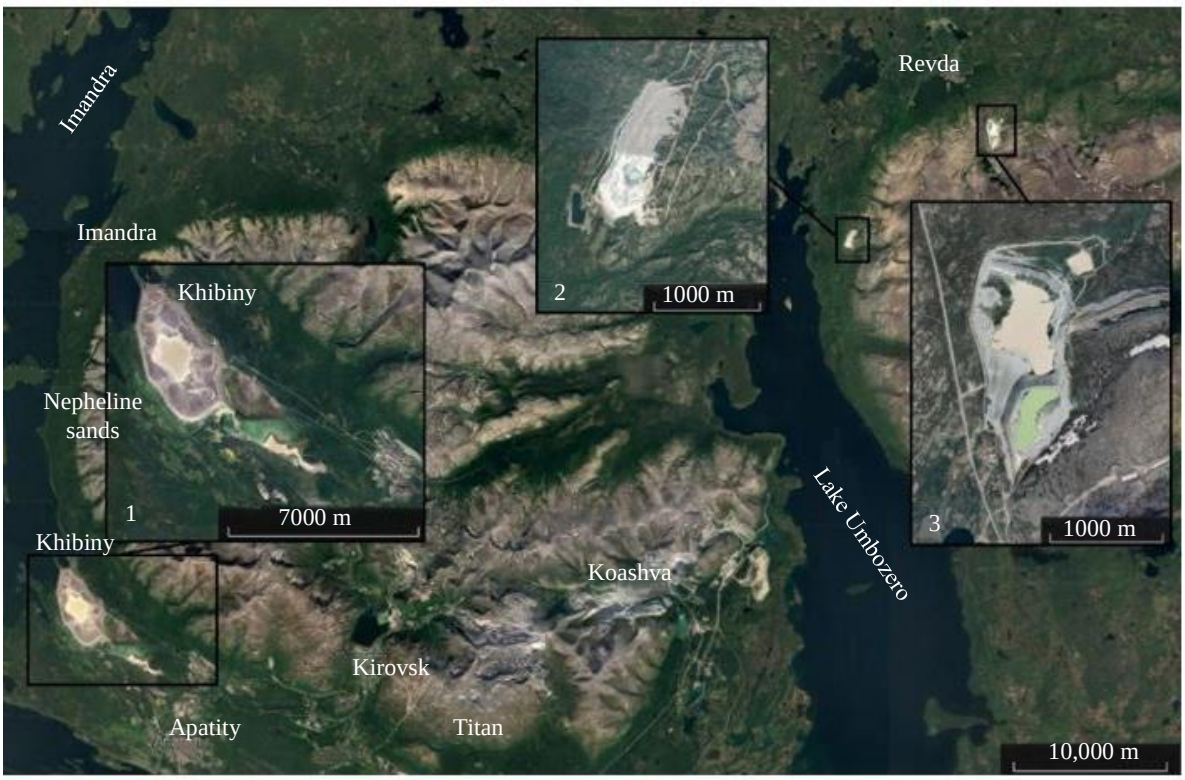


Fig.1. ANOF-3 (1), Umbozero (2), and Karnasurt-1 (3) tailings storage facilities

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Tailings samples were collected and studied earlier: engineering-geological properties (GOST 5180-2015 "Soils. Methods for Laboratory Determination of Physical Properties") and material composition were determined [30, 31]. The tailings exhibit low organic content (< 1 %) and alkaline or neutral pH values. Mineral (estimated by the Rietveld method, Geological Institute of the Kola Science Centre, RAS) and chemical (silicate analysis, OAO "Kola Geological Information Laboratory Centre") compositions of the averaged samples are presented in Tables 1 and 2.

Table 1

Mineral composition of dressing tailings, wt.%

Mineral	LT1	Mineral	LT2	Mineral	ANT
Nepheline	59-60	Nepheline	38-44	Nepheline	59-60
Feldspar	16-20	Albite	18-21	Feldspars	9.2-12
Apatite	0.65-1.01	Microcline	22-24	Apatite	5.1-6.1
Loparite	0.63-0.94	Annite	0.39-0.72	Pyroxene	17-18
Aegirine	18-20	Arfvedsonite	3.4-3.9	Sphene	3.5-3.9
Diopside	0.012-0.038	Aegirine	7.0-7.3	Magnetite	2.1-2.4
Sodalite	1.2-1.6	Loparite	0.28-0.40	Calcite	0.33-0.41
Lomonosovite	0.14-0.17	Natrolite	2.4-3.4		
Lamprophyllite	0.03-0.21	Sodalite	1.7-2.8		
Eudialyte	0.011-0.023	Quartz	0.81-1.7		

Table 2

Chemical composition of dressing tailings, wt.%

Element	Content			Element	Content		
	LT1	LT2	ANT		LT1	LT2	ANT
SiO_2	~48	54-55	42-43	MgO	0.40-0.45	0.55-0.85	1.2-1.5
TiO_2	0.85-1.1	0.71-0.88	2.5-2.7	K_2O	4.2-4.5	5.5-6.4	6.0-6.2
Al_2O_3	22-24	20-21	21-23	Na_2O	13-14	9.6-10	9.1-9.8
Fe_2O_3	5.5-6.0	4.4-5.0	3.9-4.3	P_2O_5	0.54-0.79	0.029-0.047	2.1-2.6
FeO	0.52-0.66	0.46-0.62	2.1-2.6	SrO	0.24-0.35	< 0.10	0.24-0.31
MnO	0.20-0.23	0.18-0.21	0.11-0.23	F	0.072-0.081	0.050-0.058	0.21-0.30
CaO	1.3-1.6	2.6-2.8	5.6-6.0	S	0.064-0.085	0.019-0.030	0.11-0.18

Dressing tailings represent mineral materials with low biological activity, moderate moisture capacity, and a neutral to alkaline reaction. Their properties allow consideration of these wastes as a potential raw material for reclamation, technical landscaping, and creation of technosols for biological dust suppression, provided additional enrichment with organic and nutrient components, as noted in [32, 33].

A sample of the by-product of biological wastewater treatment was provided by one of the enterprises from the Murmansk Region, where it was preliminarily kept on sludge drying beds in the open air for 2-3 years at the treatment facilities. The SS sample was sent to an accredited laboratory of the Centre for Laboratory Analysis and Technical Measurements for the Murmansk Region for chemical analysis, and to the Centre for Hygiene and Epidemiology in the Murmansk Region for parasitological and bacteriological analysis. They assessed compliance with the requirements of GOST R 54534-2011 and GOST R 59748-2021 for SS used as soil substrates for biological or technical reclamation.

According to GOST R 54534-2011, SS can be applied for biological or technical reclamation, and according to GOST R 59748-2021, if the content of at least one of the regulated elements exceeds

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the permissible level for group I, the sludge is assigned to group II. Sludges of groups I and II are used in industrial floriculture, green construction, forest and ornamental nurseries, for biological reclamation of disturbed lands, and for solid municipal waste landfills.

To assess the dose-dependent effect of the organic additive on the properties of technosol substrates and to determine the optimal ratio of components under reclamation conditions, SS was mixed with dressing tailings of apatite-nepheline (ANT) or loparite (LT1, LT2) ores in ratios of 1:9, 2:8, and 3:7, respectively (Table 3). Tailings without SS additives served as reference samples.

Table 3

Tailings-to-SS ratio and labelling of soil substrates

Soil substrate	LT1:SS				LT2:SS				ANT:SS			
	10:0	9:1	8:2	7:3	10:0	9:1	8:2	7:3	10:0	9:1	8:2	7:3
Labelling	A0	A1	A2	A3	B0	B1	B2	B3	C0	C1	C2	C3

The choice of the SS dosage range (10-30 % or 1:9, 2:8, 3:7) is justified by practical recommendations given in GOST R 54534-2011. According to clause 4.3 of this standard, a single application rate of soil substrates based on SS during reclamation can reach 200-300 t/ha. Considering the bulk density of dry SS (~0.6 g/cm^3) and nepheline tailings (~1.8 g/cm^3), the volumetric ratios of SS to tailings of 2:8 and 3:7 allow formation of a reclamation layer to 25 and 17-18 cm high, respectively, which agrees with standard practice of creating a root-inhabited layer during biological reclamation of tailings storage facilities.

Research methods. To assess the properties of the obtained technosol substrates, we determined their water-holding capacity, potential (pH of salt (KCl) extract) and actual acidity (pH of water extract after seven days), as well as the content of nutrient elements – calcium, magnesium, sodium, silicon, nitrogen, phosphorus, and potassium – in plant-available form. We determined the content of nutrient elements in an extract with 0.01 M citric acid solution, which is the dominant organic acid in soil waters of the studied area [34].

To determine the pH of the water extract, substrate aliquots of 5 g mass were placed in 50 ml of distilled water, and after seven days the pH of the suspensions was measured using a laboratory ion meter I-160MI equipped with a glass electrode ES-10603 and a reference electrode ESr-10103 (GOST 26423-85 "Soils. Methods for Determination of Specific Electrical Conductivity, pH, and Dense Residue of Water Extract"). The salt (KCl) extract for pH measurement was prepared at a solid-to-liquid ratio of 1:25 and mixed on a laboratory shaker for one hour in accordance with GOST 26483-85 "Soils. Preparation of Salt Extract and Determination of its pH by the CINAO Method".

According to the procedure described in [35, 36], to prepare the extract, 250 ml of 0.01 M citric acid solution was added to a soil aliquot of 25 g mass. The mixture was stirred for six hours on a magnetic stirrer ES6120 (ECROS) at a temperature of 20 °C. The resulting suspension was filtered through a double paper blue ribbon filter. Chemical analysis of the filtrate for the content of available nutrient elements was performed using the following methods: atomic absorption spectrometry on a Quant-2mt spectrometer (K, Na, Ca, Mg), inductively coupled plasma mass spectrometry (ICP-MS) on an Elan 9000 spectrometer (P), photometric method on a KFK 3-01 photometer (Si), and a total nitrogen and carbon analyser Topaz N (N).

To determine the maximum water-holding capacity of technosol substrates (in accordance with the requirements of GOST 32632-2014 "Test Methods for Chemical Products Hazardous to the Environment"), a sample of 5 g mass was taken with a sampling tube, the lower part of which was covered with filter paper and placed on a grid in a water bath. The tube was gradually immersed in water to a level

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above the height of the soil sample and kept for at least three hours for complete moisture saturation. Then, preliminary drying was carried out for two hours in a closed container with a substrate of moist crushed quartz sand. After conditioning, the sample was weighed, dried to constant mass at 105 °C, and weighed again to determine moisture loss.

Phytotoxicity test procedure. To assess the biological effectiveness of the developed technosol substrates, we conducted laboratory pot experiments using two test cultures – radish (*Raphanus sativus* L.) and perennial ryegrass (*Lolium perenne* L.). The choice of these species is due to their prevalence in bioassays: radish is a highly sensitive model culture that responds quickly to changes in substrate properties [37], and ryegrass is widely used in biological reclamation of disturbed lands, including the Far North, due to its resilience, intensive growth, and ability to rapidly form a sod cover [38].

Thirty radish and ryegrass seeds for each experimental variant were placed in plastic containers filled with moistened experimental substrates. Germination was carried out at a stable temperature of 20-22 °C for 21 days. Seeds were checked daily for germination, and the technosol substrate was moistened with room-temperature water as needed, avoiding overwatering. Germination rate was assessed on the tenth day, and morphometric parameters – height and fresh aboveground biomass – were measured after 21 days of cultivation.

Statistical processing of the results included computation of mean values and standard errors; significance of differences between variants was determined by one-way ANOVA at a significance level of $p < 0.05$ using Microsoft Office Excel 2016, which meets the requirements of biological and agrochemical studies [39].

Discussion

Properties of tailings and SS. Table 4 presents the physicochemical properties of the studied dressing tailings. Water-holding capacity ranges from 110 to 123 %. The highest values were recorded for LT2 tailings (123 %), and the lowest values were observed for LT1 (110 %), which is likely due to the heterogeneity of the particle size distribution and mineralogical components that determine the physical properties of the materials.

Table 4

Physicochemical properties of dressing tailings

Tailings properties	LT1	LT2	ANT
Water-holding capacity, %	110±40	123±50	120±40
Actual acidity	8.5±0.2	6.3±0.1	6.5±0.2
Potential acidity	7.9±0.2	6.1±0.1	6.3±0.1
Content of available forms of components:			
K, g/kg	0.59±0.11	0.37±0.09	0.28±0.08
Na, g/kg	1.4±0.2	1.6±0.2	2.0±0.2
Ca, g/kg	0.31±0.04	0.09±0.02	0.13±0.01
Si, g/kg	0.99±0.21	0.86±0.19	0.81±0.18
Mg, mg/kg	1.5 ± 0.16	0.72 ± 0.10	0.65 ± 0.10
N, mg/kg	1.5 ± 0.30	1.4 ± 0.29	1.5 ± 0.33
P, mg/kg	1.7 ± 0.33	1.4 ± 0.22	2.1 ± 0.36

Actual acidity of the samples varied in the pH range from 6.3 to 8.5. LT1 tailings have the most alkaline reaction (pH 8.5), which may be due to the presence of nepheline, feldspars, and sodalite containing alkali and alkaline earth elements that produce an alkaline environment upon hydrolysis. LT2 and ANT have values close to neutral conditions. The pH values create favourable conditions for using the tailings as a mineral base for reclamation substrates, since they do not create an acidic environment unfavourable for plants.

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The content of available forms of chemical elements differs significantly. The highest amounts of potassium (0.59 g/kg) and calcium (0.31 g/kg) were noted in LT1, whereas the maximum sodium content (2.0 g/kg) is characteristic of ANT. Concentrations of magnesium, nitrogen, and phosphorus are extremely low (to 2.1 mg/kg), confirming the poverty of the tailings in biogenic elements. The silicon content in the range of 0.81-0.99 g/kg indicates the predominance of silicate compounds.

A brief comparison of the chemical analysis of the SS sample with the requirements of GOST R 59748-2021 and GOST R 54534-2011 is presented in Table 5.

Table 5

Comparative analysis of the chemical composition of SS as a raw material for reclamation

Element	SS	GOST 59748-2021**	GOST R 54534-2011***
Organic matter, %	20.2±1.2	At least 20	Not provided
As, mg/kg	2.3±0.7	10 (I) -20 (II)	20 (B)-40 (T)
Cd, mg/kg	4.2±1.3	15 (I)-30 (II)	30 (B)-60 (T)
Pb, mg/kg	88±26	250 (I)-500 (II)	500 (B)-1000 (T)
Zn, mg/kg	530±160	1750 (I)-3500 (II)	3500 (B)-7000 (T)
Ni, mg/kg	160±50	200 (I)-400 (II)	400 (B)-800 (T)
Cu, mg/kg	640±190	750 (I)-1500 (II)	750 (B)-1500 (T)
Cr, mg/kg	440±130	500 (I)-1000 (II)	1000 (B)-2000 (T)
Hg, mg/kg	9.2±2.3	7.5 (I)-15 (II)	15 (B)-30 (T)
Salt extract pH	5.5±0.1	5.5 (I)-8.5 (II)	5.0-8.5
Total nitrogen, %	1.1±0.2	At least 0.6	0.5 (B)-not rated (T)
Total phosphorus, %*	0.73±0.05	At least 1.5	1.5 (B)-not rated (T)

* The result for total phosphorus is provided as P conversion factor to P_2O_5 is 1.67 %.
** I – first waste group; II – second waste group.
*** B – for use in biological reclamation; T – for use in technical reclamation.

The provided SS sample belongs to group II (according to GOST 59748-2021) and can be used for technical reclamation (according to GOST R 54534-2011). Group II sludges are used for cereal, grain legume, fodder grain, and industrial crops. Parasitological and bacteriological studies did not reveal the presence of geohelminth eggs, coliform bacteria, or pathogenic microorganisms.

Properties of the technosol substrate. The medium reaction is one of the key factors determining the suitability of a soil substrate for plant growth and development. We found that the pH of the water extract of samples after seven days varies from 6.0 to 7.9 depending on the proportion of added SS (Fig.2). With an increase in the content of the organic additive, which has a slightly acidic reaction, a decrease in pH of both water and salt extracts is observed, which is likely due to the formation of slightly acidic products of biochemical decomposition of organic matter and a decrease in the proportion of alkaline components of mineral tailings. Thus, the addition of 20-30 % SS promotes a change in pH from slightly alkaline to neutral or slightly acidic, which is optimal for most cultivated plants and microbiological processes in soil.

The addition of sewage sludge had a positive effect on the water-holding capacity of the soil substrate. With an increase in the SS proportion from 10 to 30 %, an increase in this parameter from 127 to 156 % was observed (using mixtures with LT1 tailings as an example). A similar relationship

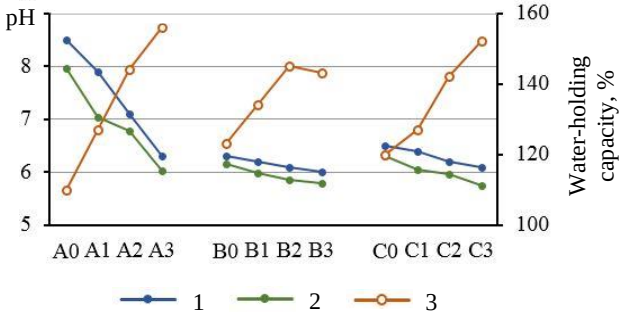


Fig.2. Values of actual and potential acidity and water-holding capacity of anthropogenic soil substrates at different SS application rates

1 – pH_{H_2O}; 2 – pH_{KCl}; 3 – water-holding capacity, %

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is characteristic of mixtures with LT2 and ANT. The increase in water-holding capacity is explained by the higher content of organic matter, which increases the overall porosity and moisture capacity of the material [40-42]. This property is particularly important for the reclamation of dry and humus-poor anthropogenic lands.

The addition of SS to the tailings led to significant changes in the chemical composition of the resulting technosol substrates (Table 6). An increase in the content of biogenic elements is observed depending on the proportion of added SS. The nitrogen concentration increased significantly when comparing reference variants with technosol substrates (tailings to SS ratio 7:3) – from 24 (series C) to 47 times (series B). A similar trend is characteristic of phosphorus – the increase in content ranged from 9 (series A) to 19 times (series B). The calcium content changed less significantly – from 1.5 (series A) to 5.3 times (series B). The data obtained indicate an improvement in the agrochemical properties of the soil substrates.

Table 6

Chemical composition of anthropogenic soil substrates

Component content	A1	A2	A3	B1	B2	B3	C1	C2	C3
K, g/kg	0.54±0.11	0.50±0.11	0.47±0.12	0.37±0.09	0.37±0.10	0.38±0.11	0.28±0.08	0.29±0.09	0.30±0.08
Na, g/kg	1.5±0.1	1.5±0.1	1.5±0.1	1.7±0.1	1.7±0.1	1.7±0.1	2.0±0.2	2.0±0.2	2.0±0.1
Ca, g/kg	0.35±0.04	0.40±0.02	0.46±0.03	0.25±0.02	0.33±0.02	0.48±0.03	0.20±0.01	0.30±0.03	0.38±0.02
Si, g/kg	0.81±0.03	0.71±0.04	0.60±0.03	0.76±0.04	0.68±0.04	0.61±0.03	0.80±0.05	0.71±0.04	0.70±0.04
Mg, mg/kg	2.8±0.37	5.1±0.82	7.0±0.70	2.5±0.25	4.6±0.64	6.6±0.86	1.8±0.35	2.4±0.50	3.4±0.58
N, mg/kg	20±3.4	48±16	62±18	24±3.1	45±9.9	66±17	24±3.8	31±5.9	36±6.8
P, mg/kg	5.4±0.86	8.9±1.2	15±1.7	6.5±1.0	19±3.6	27±4.9	7.4±1.1	20±2.6	28±6.4

Changing the tailings to SS ratio affected the silicon content – with an increase in the SS proportion, a slight decrease in Si was observed, which is associated with the dilution of the mineral phase by the organic component. For example, in series A, the Si content decreased 1.7-fold, in series B – 1.4-fold, and in series C – 1.2-fold compared to the reference sample. Similar trends are noted in some studies. The addition of SS made it possible to reduce the pH of soil samples and increase the content of biogenic elements in plant-available form after reclamation measures [43-45].

Table 7

Germination rate of test culture seeds depending on the SS content in technosol substrates

Substrate	SS content, %	Test culture	
		Radish	Ryegrass
A0	0	18.3±1.5	51.7±6.2
A1	10	52.0±4.2	60.0±7.2
A2	20	58.0±4.6	62.0±7.4
A3	30	72.0±5.8	65.0±7.8
B0	0	33.3±2.7	47.2±5.7
B1	10	48.0±3.8	57.0±6.8
B2	20	51.0±4.1	73.0±8.8
B3	30	53.0±4.2	78.0±9.4
C0	0	47.3±3.8	53.7±6.4
C1	10	67.0±5.4	57.0±6.8
C2	20	78.0±6.2	62.0±7.4
C3	30	80.0±6.4	73.0±8.8

Phytotoxicity testing is a key stage of biological assessment of the quality of the obtained technosol substrates. It is aimed at determining their ability to ensure seed germination and plant development, as well as at identifying the optimal content of the organic additive in the form of SS. The appearance of plants at the end of the experiment, seed germination rate, and changes in the morphometric parameters of test plants depending on the dosage of added SS are presented in Table 7 and in Fig.3, 4.

The experiment revealed that the germination rate of seeds of both test cultures increased as the SS proportion in the technosol substrates increased (Table 7). The minimum germination

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rates for all series were recorded in the reference variants (0 % SS). The addition of 10 % SS led to a noticeable increase in germination, and the application of a 20-30 % additive provided a statistically significant increase in the parameter ($p < 0.05$). Thus, the germination rate of radish seeds in series A increased almost fourfold, and that of perennial ryegrass – 1.7-fold (series B). The greatest effect was observed at the maximum studied SS dosage (30 %) – for radish, the maximum germination rate was achieved in series C (80.0±6.4 %), and for ryegrass – in series B (78.0±9.4 %) and C (73.0±8.8 %). Thus, an increase in the SS proportion has a positive effect on the germination of both radish and ryegrass, which is associated with the input of organic matter and plant-available nutrient elements.

Plant height during the experiment depended on the ameliorant content in the tested substrates. With an increase in the proportion of the organic additive, the average height of radish increased twofold or more, and that of ryegrass – up to threefold compared to the reference variants (Fig.3). In ryegrass, the response to the change in the amount of added SS was less pronounced – the plant height in the experimental variants based on loparite tailings was 11.5-12 cm, and based on apatite-nepheline tailings – 10-11.5 cm, regardless of the amount of added SS. However, the observed moderate tendency toward an increase in ryegrass height may also indicate a positive effect of SS on plant growth.

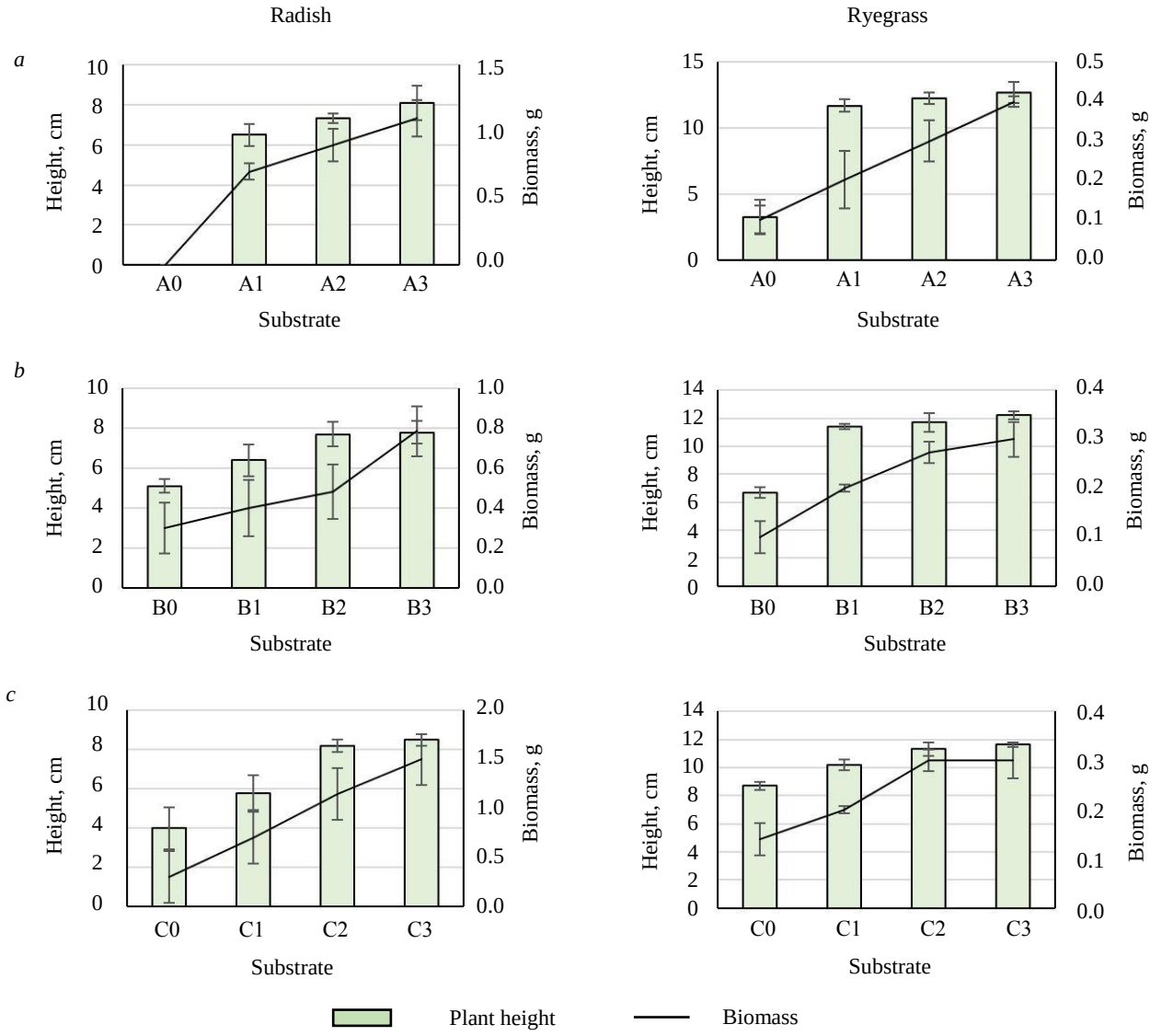


Fig.3. Height and fresh aboveground biomass of radish and ryegrass plants at different SS application rates in anthropogenic soil substrates: *a* – LT1; *b* – LT2; *c* – ANT

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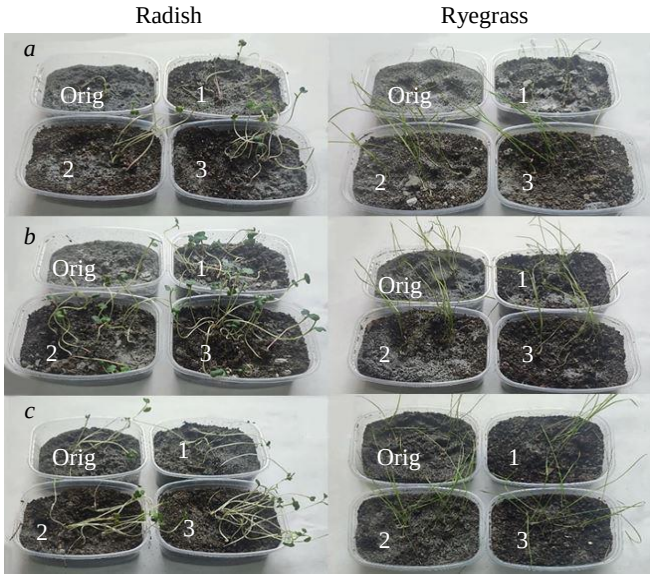


Fig.4. Appearance of radish and ryegrass plants upon completion of phytotesting: *a* – LT1; *b* – LT2; *c* – ANT

The fresh aboveground biomass of plants, which is an integrated indicator of their physiological state, also increased significantly at tailings to SS ratios of 8:2 and 7:3. In individual substrate variants, biomass increased three- to fivefold compared to the reference variants of the experiment. The difference in the growth of parameters in ryegrass compared to radish can be explained by the fact that different plant species have different nutrient requirements and conditions for optimal growth. Radish, being a sensitive crop, responds more quickly to changes in environmental conditions and actively absorbs nutrients from enriched substrates. Ryegrass is more resistant to various stressors such as drought or low soil fertility [46]. At the same time, despite the less pronounced response of ryegrass compared to radish, an increase in the SS proportion has a positive effect on its growth and development, which is confirmed by a statistically significant increase in biomass and germination rate. The stimulating effect of SS-based additives is also noted by a number of investigations based on the results of pot and field experiments [35, 47, 48].

Plant appearance. As can be seen in Fig.4, plants differ in the degree of development – from weak, stunted specimens to well-formed ones with a relatively dense aboveground part. In series A (LT1), plants appear more suppressed, with sparse emergence. In series B (LT2) – moderate density, plants are more uniform. Series C (ANT) – plants are the most vigorous, with a dense and uniform cover compared to series A and B. The appearance of the plants is consistent with the results obtained.

Differences in the morphometric parameters of test cultures for diverse types of tailings are explained by their initial physicochemical properties. In particular, LT1 tailings have higher alkalinity (pH of water extract 8.4-8.7), higher sodium content (to 13.6 % Na_2O), and lower available phosphorus and calcium content compared to LT2 and ANT tailings. For LT1 loparite tailings, further adjustment of the soil substrate formulation will be required, either by increasing the SS proportion (which, however, will reduce the height of the possible layer of soil substrate applied onto the dressing tailings) or by adding neutralizing amendments (for example, a small amount of peat) to reduce pH from 8.4-8.7 to 7.0-7.5 and increase the content of plant nutrient elements. After adding 20-30 % SS in variants A2 and A3, the medium reaction is already close to neutral (pH 6.9-7.3).

Analysis of the laboratory experiment results allows the conclusion that the addition of SS has an obvious stimulating effect on seed germination, plant height, and biomass due to changes in the physicochemical properties of the substrates – reduction of alkalinity, increase in water-holding capacity, and content of nutrient elements [49]. For practical application at tailings storage facilities, long-term field experiments are needed, based on which dosage estimations can be made considering the bulk density of the mixture and the design depth of the reclamation layer.

Conclusion

As a result of the study, a comprehensive comparative assessment of technosol substrates based on nepheline dressing tailings of the Murmansk Region with the addition of SS was conducted for the first time, and the dependence of their physicochemical properties and phytotoxicity testing parameters on the composition of the mixture was revealed. We determined the following:

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• Mixing SS with dressing tailings improves the agrochemical properties of the formed soil substrate. The addition of the organic component reduces the pH of apatite-nepheline and loparite (Umbozero tailings storage facility) tailings to neutral values (6.5-7.2), promoting better development of most crops.

• An increase in the SS application rate has a positive effect on the water-holding capacity of soil substrates. When 20-30 % SS is added, the moisture capacity increases 1.4-1.8-fold compared to the reference sample (from 18-22 to 32-38 % of the soil substrate mass), which ensures improvement of the water-air regime.

• Phytotoxicity testing results (seed germination, plant height, and biomass) showed a significant improvement in these parameters in the experimental variants, demonstrating the stimulating effect of SS on the growth and development of the tested crops.

• Chemical analysis of the technosol substrates showed that the addition of 20-30 % SS increases the content of exchangeable calcium 2.1-3.4-fold, sodium 1.2-1.6-fold, and mobile phosphorus 2.0-2.8-fold compared to the reference sample, which contributes to improved mineral nutrition of plants and increased productivity.

• For the dressing tailings of the Karnasurt tailings storage facility, additional adjustment of the formulation is required, either by increasing the SS proportion (which, however, may reduce the height of the possible layer of soil substrate applied onto the dressing tailings) or by adding neutralizing additives (for example, a small amount of peat) to reduce pH from 8.4-8.7 to 7.0-7.5 and increase the content of plant nutrient elements.

The results obtained under laboratory conditions preliminarily confirm the feasibility of implementing the method of creating technosol substrates based on dressing tailings and SS. At the same time, a field experiment is necessary, as well as monitoring the long-term impact of soil substrates on plant communities and element migration. Special attention should be paid to the selection of plants with a well-developed fibrous root system (for example, perennial ryegrass, red fescue, etc.) that contribute to the reduction of erosion processes and the formation of a dense pioneer plant cover.

This approach is of significant practical importance for the integrated solution of environmental protection and rational resource use tasks, allowing minimization of the negative consequences of mineral extraction and industrial waste disposal. The practical implementation of the proposed technology will ensure environmentally sustainable economic activity in regions with intensive exploitation of raw material reserves, including the northern regions of Russia.

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