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Production of fertilizers from wastes of various origins for the reclamation of disturbed lands and improvement of territories

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Abstract

This study addresses the loss of land for other uses resulting from economic activities and waste disposal, highlights the need to develop alternative fertilizers suitable for the biological stage of land reclamation and subsequent landscaping, and examines the resource potential of industrial wastes for producing nutrient amendments. The most promising waste processing approaches involve producing sewage sludge-based fertilizers through composting with other industrial wastes of various origins. A combined computational and experimental approach was used to develop composting mixtures, enabling optimization of the C:N, moisture content, and pH while incorporating visual assessments during laboratory trial mixing. The fertilizers produced were assessed qualitatively and quantitatively for veterinary, sanitary, hygienic, toxicological, and agrochemical parameters in accordance with applicable regulatory requirements. A plant growth experiment using artificial soil demonstrated their effectiveness in improving key plant productivity parameters, including seed germination, plant biomass, and maximum plant height. Potential factors limiting fertilizer application were identified as toxic element contents and possible imbalances between moisture retention and air exchange caused by reduced soil substrate density at high fertilizer mass fractions. These findings confirm the feasibility of reusing wastes of various origins to restore land quality and expand the range of alternative fertilizers.

Keywords

industrial wastes; waste recovery; sewage sludge; composting; fertilizers; disturbed land reclamation; landscaping

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Introduction

Rapid industrial development, high levels of mineral extraction, infrastructure development, and urbanization inevitably lead to the transformation of the Earth's surface. These anthropogenic processes give rise to a distinct class of geosystems characterized by alterations to natural landscapes and changes in the quantity and quality of environmental components. Such geosystems constitute disturbed land that has lost its original economic or ecological value [1-3].

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Disturbed land resulting from mineral extraction and the disposal of waste from various origins constitutes a major source of environmental stress worldwide. A defining feature of mining-induced land degradation is the abrupt transition to a disturbed state, accompanied by partial or complete destruction of the soil cover, alteration of the hydrological regime, and the release of pollutants, leading to rapid degradation of adjacent areas [4-6]. The most significant adverse impacts of waste disposal include the loss of extensive areas of land for other uses and long-term changes in the chemical composition of surrounding environmental media due to pollutant transport through waterborne and biogenic migration, as well as atmospheric transport [7-9].

Despite these adverse impacts, production continues to expand and improve, while consumer demand and living standards continue to rise [10, 11], inevitably leading to a proportional increase in anthropogenic pressure. At the same time, a persistent imbalance exists between the rates of land disturbance and reclamation. For example, between 2019 and 2023, mineral extraction resulted in an additional 504.6 thousand hectares of disturbed land, whereas 252.3 thousand hectares were reclaimed. Over the same period, industrial and consumer waste subjected to recovery or treatment to render it harmless accounted for an average of 46.6 % of the total waste generated[1].

These trends result in the accumulation of substantial environmental damage, with adverse effects manifested as irreversible degradation of environmental components. These effects are particularly pronounced in regions with limited capacity for natural recovery and self-purification, such as the Arctic Zone of the Russian Federation [12-14]. Thus, under increasing anthropogenic pressure, restoring the environmental stabilization and recreational functions of affected areas is essential to enhancing their ecological resilience. Taken together, these challenges highlight the need to develop and implement technologies that use waste from various origins for the rehabilitation of disturbed land and its subsequent landscaping, thereby supporting a transition to sustainable natural resource management.

Under the applicable legislation of the Russian Federation, maximizing waste recovery is one of the priorities of state policy on waste management[2], and waste recovery yielding material products is classified as a priority "green" project category[3]. Advances in waste processing technologies have enabled the production of a wide range of goods for use across various sectors of the economy [15-17]. In addressing the rehabilitation of disturbed land, particular attention is given to processing waste into fertile soils [18, 19], soil amendments, and fertilizers that can be used during the biological stage of land reclamation and subsequent landscaping [20-22].

Against the backdrop of systemic challenges associated with conventional fertilizer production, the development of alternative sources of plant nutrients is becoming increasingly important. The progressive depletion of readily accessible mineral deposits and declining ore grades necessitate increasingly complex and costly beneficiation technologies. Moreover, mineral extraction and processing entail substantial environmental costs, including those associated with the disposal of waste generated during these operations [23, 24].

[1] Environmental Protection: Statistical Compendium. Moscow: Rosstat, 2024. p. 118.

[2] Federal Law N 89-FZ of 24 June 1998 "On Industrial and Consumer Waste" (as amended by Federal Law N 495-FZ of 28 December 2025; latest version).

[3] Decree of the Government of the Russian Federation N 1587 of 21 September 2021 "On the Approval of Criteria for Sustainable (Including Green) Development Projects in the Russian Federation and Requirements for the Verification System for Sustainable Development Financing Instruments in the Russian Federation" (as amended and supplemented on 14 October 2025).

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Many agricultural and industrial wastes contain compounds of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (macronutrients), as well as essential micronutrients required for plant nutrition. For example, studies have explored the use of metallurgical slags as silicon-containing fertilizers to enhance plant stress tolerance. Waste from the fuel and energy sector can provide an additional source of calcium, phosphorus, potassium, and micronutrients [25, 26], while fertilizers derived from chemical industry waste, such as phosphogypsum or off-specification potassium chloride, are rich in calcium and sulfur or potassium, respectively [27, 28].

The main limitations of fertilizers derived from these wastes are the limited range of major nutrients they contain and their lack of organic matter, which is essential for establishing a fertile soil layer and stable plant communities on low-productivity disturbed land during reclamation and subsequent landscaping. To produce more comprehensive and balanced fertilizers, wastes containing organic matter should be considered as secondary raw materials. Existing studies primarily focus on the recovery of livestock waste (e.g., manure and poultry litter) [29, 30], processing industry waste (e.g., pulp, straw, bark, and sawdust) [31, 32], and sewage sludge (SS) [33, 34]. Among these approaches, the production of fertilizers from SS is the most promising owing to its broader and more diverse nutrient composition.

The main concerns requiring particular attention when using SS are the presence of heavy metals and pathogenic microorganisms [19, 33]. These issues can be addressed jointly through composting with various bulking agents, i.e., the aerobic fermentation of organic matter in dewatered sludge, which is included among the best available techniques (BAT)[4]. This approach supports the transition to sustainable (including "green") development in the Russian Federation[5]. It yields a product that meets toxicological and sanitary requirements by reducing heavy metal concentrations through co-composting SS with various bulking agents (a dilution effect) and inactivating pathogens during the biothermal decomposition of organic matter. Expanding the range of bulking agents through the use of industrial waste is therefore an important task that promotes greater waste recovery and supports the transition to a circular economy. Accordingly, this study aims to produce fertilizers from waste of various origins that are suitable for use during the biological stage of land reclamation and subsequent landscaping, in compliance with applicable regulatory requirements and standards.

Methods

The experimental study used SS (classified under code 72222112395 of the Federal Waste Classification Catalogue (FWCC) as dewatered sludge from biological treatment facilities for domestic and mixed wastewater, virtually non-hazardous). This sludge is a hazard class V waste generated by domestic and mixed wastewater treatment facilities. It consists of a mixture of organic and mineral components separated during wastewater treatment by sedimentation, together with a microbial consortium involved in biological wastewater treatment and subsequently removed from the treatment process.

One of the main concerns associated with the use of SS is the presence of heavy metals. Preliminary analyses showed the following concentrations: lead (Pb) – 13±6; cadmium (Cd) – 0.48±0.22; zinc (Zn) – 350±90; copper (Cu) – 290±70; nickel (Ni) – 8.8±2.2; chromium (Cr) – 210±50; mercury (Hg) – 0.27±0.07; and arsenic (As) – less than 0.2 mg/kg. Analyses were

[4] Wastewater treatment in manufacture of products (goods), performance of works and provision of services in large enterprises. ITS NDT 8-2022. Moscow: NDT Bureau, 2022, p. 93 (in Russian).

[5] Decree of the Government of the Russian Federation N 1587 of 21 September 2021 "On the Approval of Criteria for Sustainable (Including Green) Development Projects in the Russian Federation and Requirements for the Verification System for Sustainable Development Financing Instruments in the Russian Federation" (as amended and supplemented on 14 October 2025).

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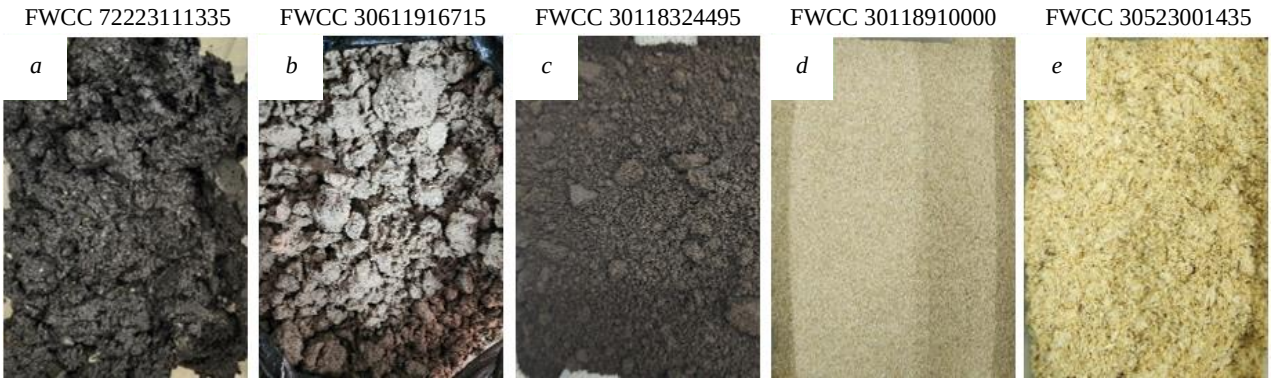


Fig.1. Appearance of the investigated wastes: *a* – sludge from biological treatment facilities for domestic and mixed wastewater, dewatered to 80 %; *b* – dewatered mixture of wastes from the repulping, cleaning, and sorting of recovered paper and pulp during paper stock preparation; *c* – crushed particles of a semi-finished coffee product; *d* – animal feed waste; *e* – clean wood sawdust

performed using an MGA-1000 atomic absorption spectrometer (Lumex) in accordance with analytical method M 09-02-2016 and an RA-915Lab mercury analyzer (Lumex) in accordance with analytical method M 03-10-2022. These results were taken into account when determining the optimal mixtures for composting.

Industrial wastes of various origins were investigated as potential bulking agents for SS composting:

• a dewatered mixture of wastes from the repulping, cleaning, and sorting of recovered paper and pulp during paper stock preparation (FWCC code 30611916715), classified as a hazard class V waste from the pulp and paper industry. This waste is generated during recovered paper stock preparation and is characterized by a high content of cellulose fibers, which provide the carbon required for fermentation during composting. Cellulose fibers are readily decomposed by microorganisms, improve the porosity and aeration of the composting material, retain moisture, and prevent putrefaction;

• crushed particles of a semi-finished coffee product (FWCC code 30118324495), classified as a hazard class V waste from instant coffee production and generated during the grinding and extraction of coffee beans. These particles are characterized by a high fiber content, which also provides a source of carbon, and contain nutrients (nitrogen, potassium, magnesium, and phosphorus) and various micronutrients;

• animal feed waste (FWCC code 30118910000), consisting of grain residues classified as hazard class IV waste and generated during the cleaning of processing lines in compound feed production. This waste is characterized by a high content of protein, vitamins, and micronutrients and provides a source rich in both carbon and nitrogen;

• clean wood sawdust (FWCC code 30523001435), classified as a hazard class V waste generated during wood processing at woodworking and wood processing facilities. This waste is rich in organic compounds (such as cellulose and lignin) that are readily available to microorganisms and also contains potassium, phosphorus, nitrogen, and micronutrients. During composting, mineralization converts these nutrients into plant-available forms. Owing to their high carbon-to-nitrogen ratio (C:N), sawdust is traditionally used as a bulking agent for SS composting.

The appearance of the investigated wastes is shown in Fig.1.

Empirical evidence [19, 35] and regulatory documents[6] indicate that effective waste co-composting requires the mixture to meet the following conditions: a moisture content of 40-70 % (optimum 60 %);

[6] GOST R 70083-2022. Resource Conservation. Waste Management. Guidelines for Food Waste Management.

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C:N of 25:1-35:1; and a pH (active acidity) of 6-9 (optimum: 7-8). Accordingly, the first stage of the study involved assessing these parameters in the selected industrial wastes at the Scientific Center "Assessment of Technogenic Transformation of Ecosystems" at Saint Petersburg Mining University. Table 1 presents the results (with C and N contents reported on a moisture content), together with the methods and equipment used. Measurement errors for all results reported in this study are provided in accordance with the respective measurement procedures. For determinations performed in accordance with equipment user manuals, the metrological characteristics of the equipment used are reported.

Table 1

Key characteristics of industrial wastes for composting

Component	C content, wt.%*	N content, wt.%*	C:N*	pH_{aq}**	Moisture content, wt.%***
SS	7.2	1.00	~ 7:1	7.5±0.1	80
Paper stock preparation waste	17.3	0.05	~ 345:1	7.2±0.1	59
Crushed particles of a semi-finished coffee product	21.5	0.56	~ 38:1	6.0±0.1	65
Animal feed waste	41.5	2.30	~ 18:1	8.1±0.1	13
Clean wood sawdust	26.1	0.02	~ 1300:1	5.5±0.1	55

* LECO CHN-628C carbon, hydrogen, and nitrogen analyzer, operated in accordance with the user manual (maximum permissible error for C and N determination ±3 % of the reference value).

** Expert-001 pH-ion-meter, used in accordance with PND F 16.2.2:2.3:3.33-02.

*** Shimadzu MOC-120H moisture analyzer, operated in accordance with the user manual (maximum permissible absolute measurement error for a 1.0 g test portion ±0.05 %).

Based on the results obtained, theoretical composting mixtures were calculated by varying the mass fractions of individual waste types to meet the acceptable ranges for all three parameters. One of the study objectives was the recovery of SS as the main component. Previous research [19] and preliminary calculations of theoretical mixtures indicated that an SS mass fraction of at least 30 % provides a sufficient potential contribution of plant nutrients, while the main factors limiting composting, such as high moisture content and a low C:N, can be mitigated by combining SS with the investigated bulking agents. The addition of clean wood sawdust was considered only when the required C:N could not be achieved using the other investigated wastes, since sawdust is a valuable secondary raw material used across various sectors of the economy.

Trial mixing was then performed under laboratory conditions to visually assess the theoretical mixtures. This stage was necessary owing to the specific characteristics of the wastes used, particularly paper stock preparation waste and crushed particles of a semi-finished coffee product.

Paper stock preparation waste is a heterogeneous fibrous material containing residual adhesives and polymer films, which may cause mixture clumping, restrict air penetration into the composting pile, and consequently promote anaerobic processes. Laboratory trials showed that a waste content below 30 wt.% did not yield optimal values for the C:N and moisture content of the composting material, whereas a content above 55 wt.% led to clumping and a reduction in pore space 5 days after mixing under laboratory conditions.

Crushed particles of a semi-finished coffee product exhibit extensive mold growth when exposed to air owing to their high moisture content and the presence of organic matter that provides a favorable nutrient source for mold colonies. Laboratory trials showed that a waste content above 35 wt.%

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resulted in extensive mold growth five days after mixing under laboratory conditions. This combined computational and experimental approach, together with the heavy metal concentrations in SS, enabled the selection of the five most suitable composting mixtures (Table 2) [36].

Table 2

Characteristics of composting mixtures for fertilizer production

Mixture	Component proportions, wt.%	C:N	pH_{aq}	Moisture content, wt.%
1	SS : paper stock preparation waste : crushed particles of a semi-finished coffee product : animal feed waste – 35:45:15:5	~ 27:1	7.2±0.1	65
2	SS : paper stock preparation waste : crushed particles of a semi-finished coffee product : animal feed waste – 30:30:35:5	~ 27:1	7.0±0.1	65
3	SS : paper stock preparation waste : animal feed waste – 35:55:10	~ 27:1	7.4±0.1	62
4	SS : paper stock preparation waste : crushed particles of a semi-finished coffee product – 35:45:20	~ 30:1	7.1±0.1	67
5	SS : crushed particles of a semi-finished coffee product : clean wood sawdust – 30:35:35	~ 35:1	6.5±0.1	66

The composting piles were formed during summer on an outdoor site with a soil surface. The appearance of the composting mixtures is shown in Fig.2.

After pile formation, the mixtures were composted with turning every 10 days to enhance or maintain heat and mass transfer and biochemical oxidation, and to shorten the composting period through pile aeration. The duration and endpoint of the active composting stage were determined by the onset of a sustained decline in the temperature inside the pile following turning, with the temperature subsequently approaching ambient levels. This indicated the completion of biothermal decomposition and the onset of maturation and humification (the passive stage). Portable Thermochron (iButton) data loggers were used to detect the onset of self-heating in the mixtures and continuously monitor the temperature inside the piles.

Following the active composting stage, the piles were left on the outdoor site with a soil surface for 30 days without turning to allow natural maturation and humification.

The fertilizers produced were assessed qualitatively and quantitatively in accordance with GOST R 54651-2011 “Organic Fertilizers Based on Sewage Sludge. Specifications”. Samples were collected to assess veterinary, sanitary, and hygienic parameters (the sanitary indicator microorganism index; the presence of pathogenic and disease-causing microorganisms; viable helminth eggs and larvae; cysts of pathogenic intestinal protozoa; and larvae and pupae of synanthropic flies), as well as for laboratory analyses of toxicological and agrochemical parameters. Given the intended application, the measured values were compared with the limits specified for Group II fertilizers, which are used for roadside forestry plantings, forest and ornamental plant nurseries, floriculture, improvement of depleted soils, reclamation of disturbed land and road embankment slopes, and landfill reclamation.



Fig.2. Compostable mixtures

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Veterinary, sanitary, and hygienic parameters were assessed by the Center for Hygiene and Epidemiology in Saint Petersburg and the Leningrad Region. Toxicological and agrochemical parameters were assessed at the Research Center "Assessment of Anthropogenic Transformation of Ecosystems" at Saint Petersburg Mining University.

The toxicological parameters monitored in accordance with GOST R 54651-2011 included the total contents of heavy metals, namely lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), nickel (Ni), chromium (Cr), arsenic (As), and mercury (Hg). Analyses were performed using an MGA-1000 atomic absorption spectrometer (Lumex) in accordance with GOST R 53218-2008 and analytical method M 09-02-2016, and an RA-915Lab mercury analyzer (Lumex) in accordance with analytical method M 03-10-2022.

The following agrochemical parameters were determined in accordance with GOST R 54651-2011: moisture content, using a Shimadzu MOC-120H moisture analyzer in accordance with the user manual; organic matter content, using a LECO TGA701 thermogravimetric analyzer in accordance with GOST 27980-88; hydrogen ion activity in a salt suspension (exchangeable acidity), using an Expert-001 pH-ion-meter in accordance with GOST 27979-88; and nutrient contents, including total nitrogen (N) and total phosphorus (expressed as P_2O_5), using a HACH DR5000 spectrophotometer in accordance with GOST 26715-85 and GOST 26717-85, respectively, and total potassium (expressed as K_2O), using a Shimadzu AA-7000 atomic absorption spectrometer in accordance with GOST 26718-85.

The feasibility of pelletizing the fertilizers produced was investigated to assess their suitability for storage and transportation. Pellets were produced from fertilizers pre-moistened until clumping occurred, using an experimental setup consisting of an MS2-150 meat grinder fitted with a die with 5 mm openings. To obtain the final product, the pellets were dried in a LOIP LF-60/350-VS-2 drying oven at 105±5 °C.

The effectiveness of the fertilizers produced was evaluated in a plant growth experiment by measuring seed germination, plant biomass, and maximum plant height following fertilizer addition to a standardized soil at different mass ratios. Artificial soil prepared in accordance with GOST R ISO 18763-2019, consisting of finely ground sphagnum peat (5 wt.%), kaolinite clay (10 wt.%), and quartz sand (85 wt.%), was used both as the standardized soil for fertilizer addition and as the control soil (without fertilizer addition). Perennial ryegrass (*Lolium perenne*), a lawn grass species, was used as the test plant.

Fertilizers were added to the standardized soil at 25, 50, and 75 wt.% on an oven-dry basis. Each substrate treatment, including the control soil, was prepared in triplicate to obtain mean results. Uniform growing conditions were maintained using an NLO 79-03-04 LD plant growth rack with adjustable lighting power and daily photoperiod (16 h light and 8 h dark). Throughout the plant growth experiment, substrate moisture was maintained at 60 % of the maximum water-holding capacity.

The manufacturer's recommended sowing rate for perennial ryegrass is 30-50 g/m^2; the midpoint of this range, 40 g/m^2, was used in the experiment. Key stages of early growth were recorded through visual observations during the plant growth experiment. Seed germination was assessed on day 10 in accordance with the recommendations of GOST 12038-84. By day 14, no new seedlings had emerged, and signs of the onset of tillering (the appearance of lateral shoots) were observed, indicating plant adaptation to the growing conditions. The experiment was terminated to prevent potential adverse effects on plant growth arising from the limited substrate volume in the containers. Thus, the plant growth experiment lasted 14 days, which was sufficient to reach the relevant experimental endpoints within the scope of this study.

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Plant biomass and maximum plant height were determined at the end of the plant growth experiment by cutting the plants 1 cm above the substrate surface. The harvested plants were then weighed using a Sartorius CP153 laboratory balance (absolute measurement error: ±5 mg), and the length of the tallest plant's green portion in each container was measured using graph paper (absolute measurement error: ±0.5 mm).

For each substrate treatment, standard deviations (SD) across replicates were calculated for seed germination, plant biomass, and maximum plant height. Student's *t*-test (testing the hypothesis of equal means in two groups) was used to assess the statistical significance of the trends observed following the addition of different doses of the fertilizers produced to the standardized soil. Pairwise comparisons were performed between the control soil without fertilizer addition and the treatments with fertilizer doses of 25, 50, and 75 wt.%, respectively, as well as between the 25 and 50 wt.% treatments and between the 50 and 75 wt.% treatments.

The bulk density of the fertilizers and standardized soil was also measured using the calibrated container method, since this parameter may affect plant growth and development as the proportion of waste-derived biocomposts in the soil substrate increases, owing to an imbalance between moisture retention and air exchange [19].

Discussion of the results

Temperature measurements showed that self-heating of the mixtures began, on average, 18-20 h after pile formation. Maximum temperatures were reached on day 4 for mixtures 1-3 and on day 3 for mixtures 4 and 5, presumably owing to the higher C:N in the latter mixtures, which affected the onset of fermentation. Peak temperatures exceeded 60 °C, suggesting the inactivation of most pathogenic microorganisms and weed seeds.

The intensification of biothermal decomposition following turning every 10 days was most pronounced in mixtures 1-3. In mixture 2, mean daily temperatures increased steadily from day 30 to day 50, with no apparent decline. Mixtures 4 and 5 exhibited relatively stable mean daily temperatures after 20 days of composting, which may indicate sufficient air exchange within the piles even without turning. Across all mixtures, mean daily temperatures ranged from 35 to 65 °C after the initial temperature peaks and subsequent decline.

Data retrieved from the loggers 60 days after pile formation revealed a sharp decline in mean daily temperatures. To confirm the end of the active composting stage, the piles were turned once more. By day 70, mean daily temperatures inside the piles were found to be close to the ambient air temperature.

Subsequent data retrieved from the loggers showed that the temperature of the composting material during maturation and humification exhibited minor fluctuations associated with changes in ambient temperature. The total composting period, including the active and passive stages, was 100 days. Fig.3 presents the temperature profiles for each mixture, excluding periods of pile turning.

According to the test reports for veterinary, sanitary, and hygienic parameters, no pathogenic or disease-causing microorganisms, viable helminth eggs or larvae, cysts of pathogenic intestinal protozoa, or larvae or pupae of synanthropic flies were detected in any of the potential fertilizer formulations. The sanitary indicator microorganism index (coliforms and enterobacteria) was below 1 cell/g, meeting the limits for Group II fertilizers specified in GOST R 54651-2011 and indicating the sanitary and epidemiological safety of the products obtained from waste processing.

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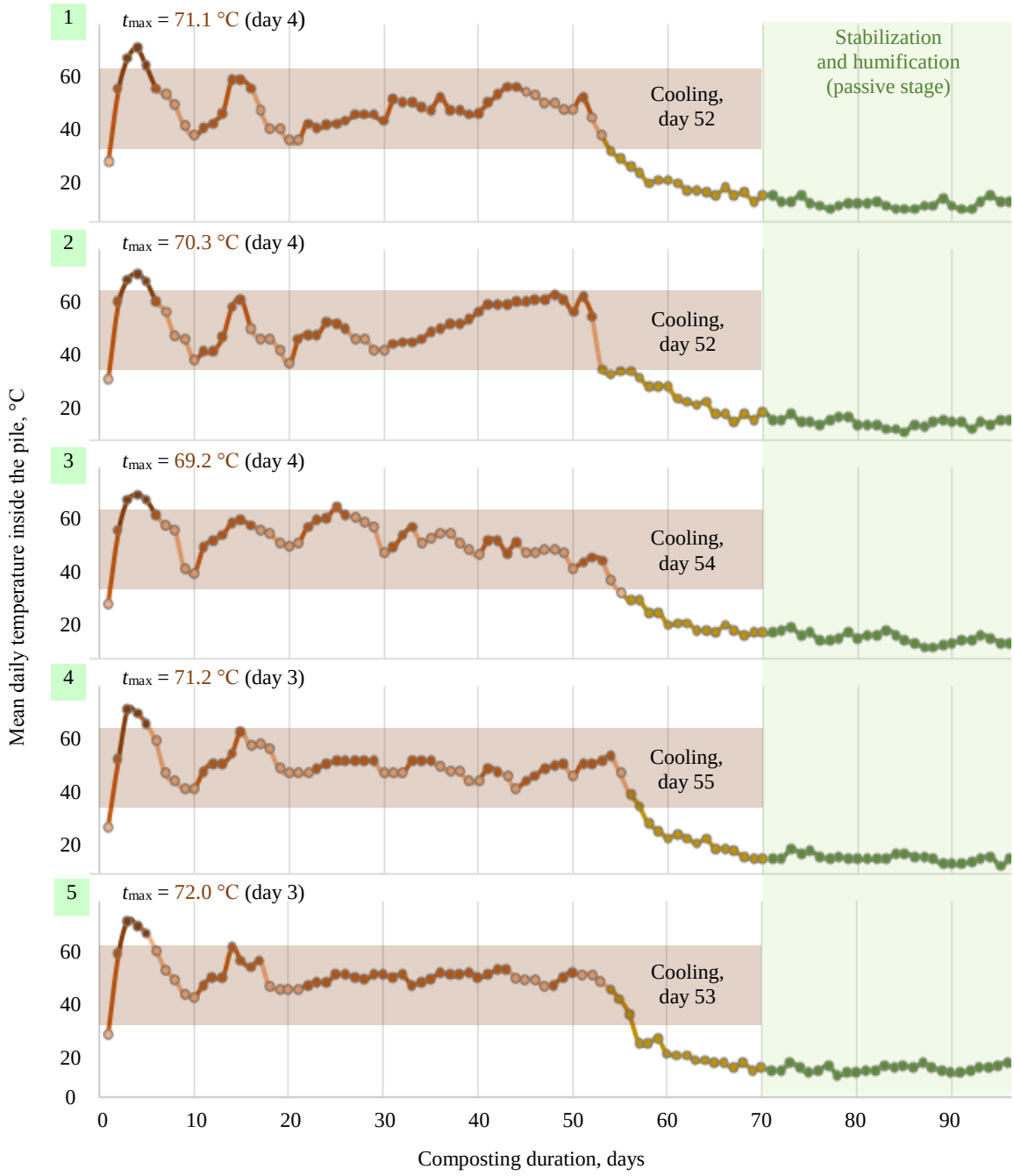


Fig.3. Composting temperature profiles for the fertilizer formulations

The assessment of toxicological parameters showed that the total contents of toxic elements in the potential fertilizers were well below the maximum permissible limits specified in GOST R 54651-2011 (Table 3). The application of these fertilizers to soil is therefore theoretically expected to pose no risk of soil microbiome degradation, reduced enzymatic activity, phytotoxicity, or morphological and functional abnormalities in plants.

The assessment of agrochemical parameters revealed no deviations from the established limits, while elevated contents of total nitrogen and total potassium (expressed as K_2O) were observed. Thus, the fertilizers produced represent a valuable potential source of nutrients that can be converted into plant-available forms through biotic transformations.

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Table 3

Characteristics of the fertilizers in terms of toxicological and agrochemical parameters

Parameters	Fertilizer formulation					Limits for Group II fertilizers specified in GOST R 54651-2011
	1	2	3	4	5	
Toxicological parameters (total contents of toxic elements, mg/kg dry matter)						
Lead (Pb)	4.5±1.6	4.1±1.4	4.7±1.6	4.3±1.5	3.4±1.2	Not more than 250
Cadmium (Cd)	0.31±0.11	0.14±0.05	0.21 ±0.07	0.18±0.06	0.17±0.06	Not more than 15
Zinc (Zn)	205±50	190±40	220±60	210±50	140±29	Not more than 1750
Copper (Cu)	140±29	130±27	150±30	165±30	100±21	Not more than 750
Nickel (Ni)	0.77±0.27	0.9±0.3	0.82±0.29	0.9±0.3	0.9±0.3	Not more than 200
Chromium (Cr)	76±19	86±22	65±16	88±22	87±22	Not more than 500
Mercury (Hg)	0.12±0.03	0.11±0.03	0.089±0.024	0.090±0.024	0.081±0.022	Not more than 7.5
Arsenic (As)	Less than 2.0	Less than 2.0	Less than 2.0	Less than 2.0	Less than 2.0	Not more than 10
Agrochemical parameters						
Moisture content, %	3.3	3.4	2.8	3.4	3.8	Not more than 70
Organic matter content on a dry matter basis, %	31.6±1.2	30.8±1.2	30.3±1.2	32.0±1.2	36.7±1.2	Not less than 30
Hydrogen ion activity in a salt suspension, pH units	7.0±0.3	6.8±0.3	7.3±0.3	6.7±0.3	6.5±0.3	6.0-8.0
Total nitrogen content on a dry matter basis, %	1.1±0.2	1.3±0.2	0.9±0.1	1.2±0.2	1.2±0.2	Not less than 0.6
Total phosphorus content on a dry matter basis (expressed as P_2O_5), %	1.00±0.05	1.00±0.05	0.90±0.05	0.80±0.05	0.80±0.05	Not less than 0.7
Total potassium content on a dry matter basis (expressed as K_2O), %	1.8±0.1	2.0±0.1	1.8±0.1	1.6±0.1	2.2±0.1	Not less than 0.1

The assessment of pelletization feasibility showed that all fertilizer formulations were capable of forming agglomerates that facilitate storage and transportation to the intended site of use (Fig.4).

The plant growth experiment (Fig.5) showed that adding the fertilizers produced to the standardized soil increased seed germination and plant productivity. At fertilizer doses of 25 and 50 wt.%, seed germination increased by an average of 12 and 15 %, plant biomass by 34 and 42 %, and maximum plant height by 28 and 30 %, respectively, indicating a slight improvement with increasing fertilizer content. At a dose of 75 wt.%, the average increases in seed germination, plant biomass, and maximum plant height were 6, 15, and 14 %, respectively, indicating a decline relative to substrates with lower fertilizer contents (Fig.6). Across replicates of each substrate treatment, the relative SD did not exceed 3.5 rel.% for seed germination, 4.9 rel.% for plant biomass, and 3.0 rel.% for maximum plant height.



Fig.4. Appearance of the fertilizers before (*a*) and after (*b*) pelletization

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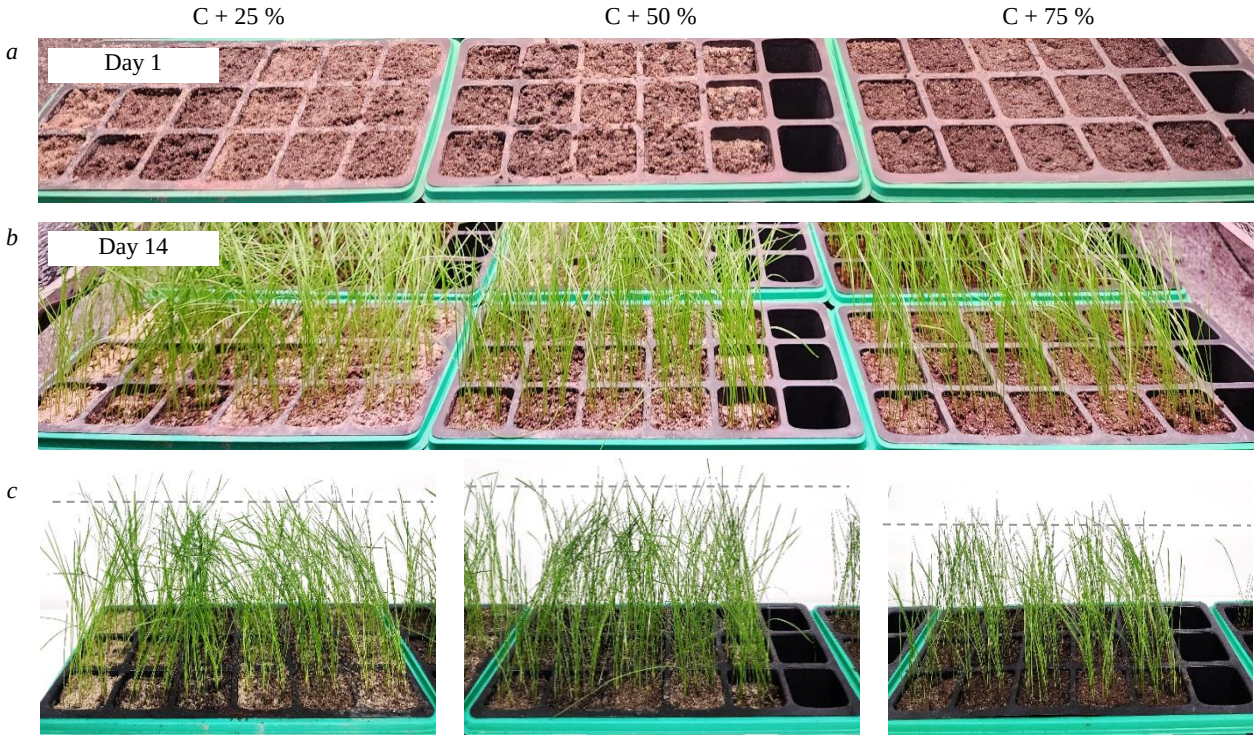


Fig.5. Appearance of the experimental substrates on days 1 (*a*) and 14 (*b*) of the plant growth experiment, and visual comparison of the height of the green plant parts on day 14 (*c*). C – control soil

Student's *t*-test was used to assess the statistical significance of the trends observed at different fertilizer doses. Pairwise comparisons between the standardized soil without fertilizer addition (control soil) and the treatments with fertilizer doses of 25, 50, and 75 wt.% confirmed statistically significant differences in mean values ($p < 0.05$) for all parameters investigated. The exception was fertilizer formulation 3 at a dose of 75 wt.%, for which only slight increases in the number of germinated seeds (approximately 5 % relative to the control soil) and plant biomass (approximately 7 % relative to the control soil) were observed, with *p*-values of 0.113 and 0.165, respectively.

Pairwise comparisons between substrates amended with 25 and 50 wt.% of the fertilizers produced revealed no statistically significant differences in any of the parameters investigated across all fertilizer formulations ($p \geq 0.05$), except for plant biomass in formulations 2 and 3. For these formulations, the *p*-values were approximately 0.03, below the significance level of 0.05, with an average relative increase in biomass of 9 rel.%.

At a fertilizer dose of 75 wt.%, a decline in all parameters investigated was confirmed, as pairwise comparisons with substrates containing 50 wt.% yielded *p*-values < 0.05 for all fertilizer formulations.

The observed results may be explained by several factors. Increasing the fertilizer proportion in the experimental substrates increases both nutrient and toxic element contents. Although the fertilizers produced comply with the applicable standard, their application to soil above a certain rate may result in exceedances of maximum permissible concentrations (MPC) and approximate permissible concentrations (APC). These soil limits are several times lower than the maximum permissible contents in Group II sewage sludge-based fertilizers specified in GOST R 54651-2011. For example, zinc (Zn) and copper (Cu) contents in the fertilizers produced ranged from 140 to 220 and from 100 to 165 mg/kg, respectively, whereas the APC specified in SanPiN 1.2.3685-21 range from 55 to 220 mg/kg for zinc and from 33 to 132 mg/kg for copper, depending on soil type. It may therefore

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be hypothesized that initial signs of phytotoxicity occur at a fertilizer content of 50 wt.% in the experimental substrates but are offset by the high content of essential nutrients, whereas a content of 75 wt.% results in more sustained toxic effects on plants.

In addition to changes in chemical composition, increasing the fertilizer proportion causes a proportional decrease in the bulk density of the experimental substrates, since the bulk density of the fertilizers (0.3-0.4 g/cm^3) differs substantially from that of the standardized soil (~1.0 g/cm^3), leading to an imbalance between moisture retention and air exchange.

The fertilizers produced from sewage sludge and wastes of various origins through aerobic fermentation during composting were shown to comply with existing requirements, and their effectiveness was confirmed by key plant productivity parameters in the plant growth experiment. However, since the experiment was conducted using artificial soil unaffected by anthropogenic impacts, the application of these fertilizers at actual sites requires a preliminary comprehensive soil assessment, primarily of toxic element contents, and selection of an optimal application rate to avoid phytotoxicity during the establishment of a stable plant community.

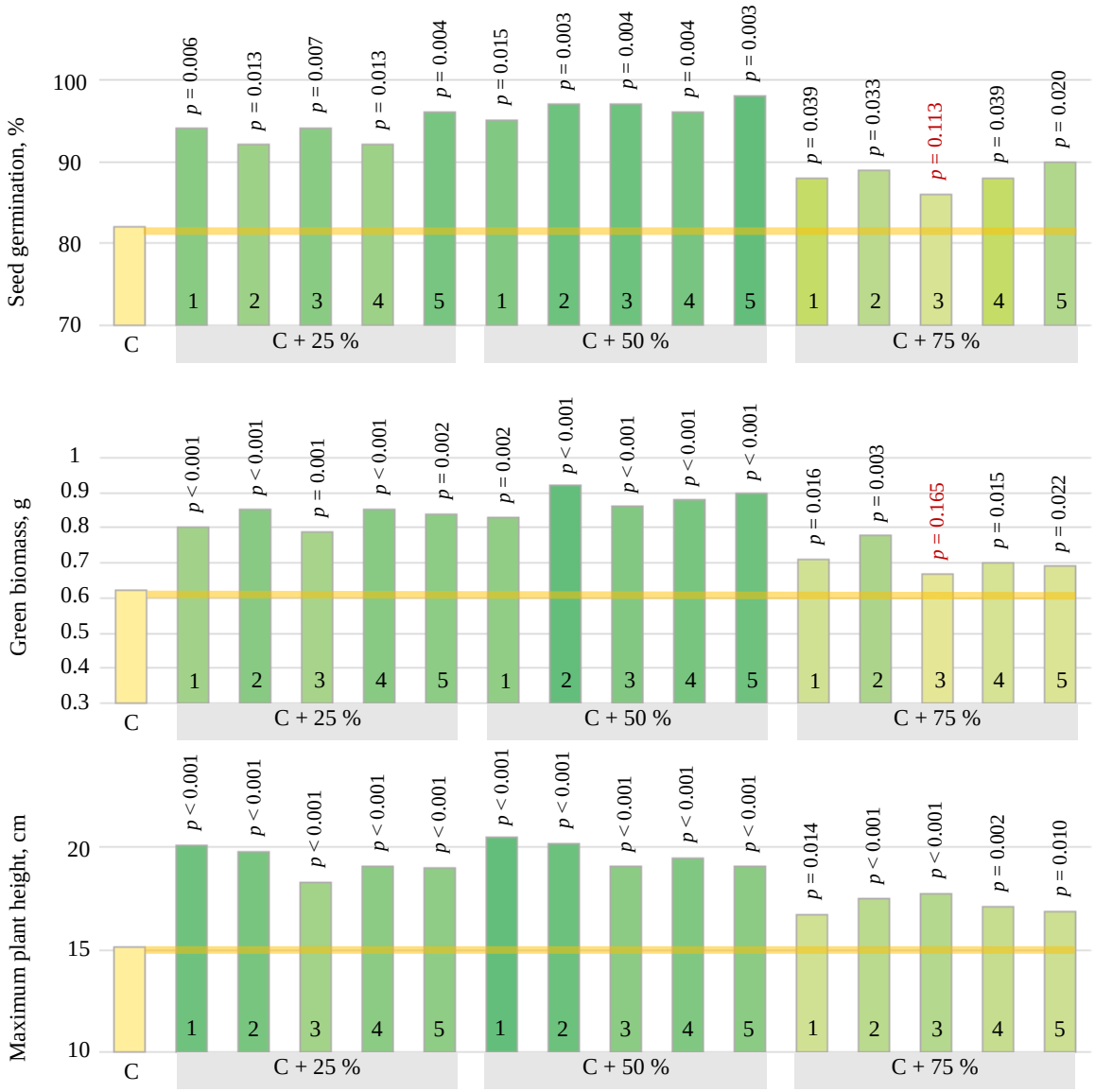


Fig.6. Results of the plant growth experiment, with *p*-values for pairwise comparisons of each treatment with the control soil

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Conclusion

Industrial wastes, while exerting substantial adverse impacts on all environmental components, represent a vast potential reservoir of nutrients and micronutrients that can be recovered. The five fertilizer formulations produced by co-composting SS with bulking agents, including paper stock preparation waste, crushed particles of a semi-finished coffee product, animal feed waste, and clean wood sawdust, fully meet the veterinary, sanitary, hygienic, toxicological, and agrochemical requirements for Group II fertilizers specified in GOST R 54651-2011 and can be used during the biological stage of land reclamation and subsequent landscaping.

The transition from waste accumulation and landfilling, which result in the loss of resource potential, to waste processing into marketable products such as fertilizers is one way to promote sustainable development and natural resource management. Advancing these technologies enables the production of alternative multinutrient amendments while addressing accumulated environmental damage and accelerating the restoration of land that has lost its fertility.

However, the use of waste as a secondary raw material requires particular attention to ensuring its safe application and balancing beneficial effects against potential risks, as demonstrated by the plant growth experiment. Further research should therefore investigate the application of the fertilizers produced to soils in anthropogenic landscapes.

REFERENCES

1. Gavrilov V.L., Nemova N.A., Reznik A.V. et al. On the need for a comprehensive geoecological assessment of lands disturbed by mining. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering.* 2023. Vol. 334. N 10, p. 76-87 (in Russian). DOI: 10.18799/24131830/2023/10/4212

2. Zenkov I.V., Pereira E.G., Conde A.S. et al. Study of Ecological Damage to Natural Landscapes after the Closure of Coal Mines in the Tula Region. *Ecology and Industry of Russia.* 2025. Vol. 29. N 1, p. 16-21 (in Russian). DOI: 10.18412/1816-0395-2025-1-16-21

3. Dziuba E. Technogenesis influence on a geochemical feature of soils: review of modern concepts. *Anthropogenic Transformation of Nature.* 2024. Vol. 10. N 2, p. 20-41 (in Russian). DOI: 10.17072/2410-8553-2024-2-20-41

4. Quansheng Li, Junting Guo, Fei Wang, Ziheng Song. Monitoring the Characteristics of Ecological Cumulative Effect Due to Mining Disturbance Utilizing Remote Sensing. *Remote Sensing*. 2021. Vol. 13. Iss. 24. N 5034. DOI: 10.3390/rs13245034

5. Simonova Yu.V., Zhunusova O.R., Charykova M.V., Kasatkina G.A. Soil-geochemical assessment of salinization of the territory adjacent to the Kuchuk salt deposit (Altai Krai). *Vestnik of Saint Petersburg University. Earth Sciences.* 2024. Vol. 69. Iss. 1, p. 185-212 (in Russian). DOI: 10.21638/spbu07.2024.110

6. Paramonov G.P., Kovalevskyi V.N., Mysin A.V. Determination of the Conditions of an Effective Functioning of Elongated Cumulative Charges in Processing the Marble Stone. *Key Engineering Materials*. 2020. Vol. 836, p. 19-24. DOI: 10.4028/www.scientific.net/KEM.836.19

7. Evseeva I.S., Ushakova O.V., Rusakov N.V., Alekseev M.M. Sanitary and chemical assessment of the impact of landfills on soil quality. *Gigiena i sanitariya.* 2024. Vol. 103. Iss. 10, p. 1105-1110 (in Russian). DOI: 10.47470/0016-9900-2024-103-10-1105-1110

8. Kutepova N.A., Kutepov Yu.I., Vasilieva A.D., Kutepov Yu.Yu. Impact exerted on stability of dump bottoms by waterproofing using geosynthetic materials (geomembranes). *Mining Informational and Analytical Bulletin.* 2025. N 1, p. 47-65 (in Russian). DOI: 10.25018/0236_1493_2025_1_0_47

9. Plokhov A.S., Kharko P.A., Pashkevich M.A. Effect of tailings storage facility on surface water at copper-pyrite deposit. *Mining Informational and Analytical Bulletin.* 2021. N 4, p. 57-68 (in Russian). DOI: 10.25018/0236_1493_2021_4_0_57

10. Belyaeva L.A., Rakova K.V. Russian Society in 1990-2023: An Empirical Assessment of Social Structure, Life Quality, and Socio-Psychological Climate. *Monitoring of Public Opinion: Economic and Social Changes.* 2025. N 1, p. 29-56 (in Russian). DOI: 10.14515/monitoring.2025.1.2658

11. Murphy R.H. The clear expectation of cultural betterment in the face of rising living standards. *Rationality and Society*. 2023. Vol. 35. Iss. 3, p. 338-365. DOI: 10.1177/10434631231177810

12. Danilov A.S., Kremcheev E.A., Lozovaya A.S., Gaydak V.O. Monitoring soil pollution in the town of Monchegorsk: Causes and consequences. *Mining Informational and Analytical Bulletin.* 2025. N 9, p. 53-66 (in Russian). DOI: 10.25018/0236_1493_2025_9_0_53

13. Yurkevich N.V., Eltsov I.N., Gureev V.N. et al. Technogenic effect on the environment in the Russian Arctic by the example of the Norilsk industrial area. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering.* 2021. Vol. 332. N 12, p. 230-249 (in Russian). DOI: 10.18799/24131830/2021/12/3207

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14. Dmitrieva D.M., Chanysheva A.F. Contribution of mining companies to the sustainable development of the mineral resource base of the Arctic region: A new approach to ranking key actors and assessing their interaction. *The North and the Market: Forming the Economic Order*. 2024. N 2, p. 71-87 (in Russian). DOI: 10.37614/2220-802X.2.2024.84.006

15. Jun Sheng, Hong Chen, Xin Yu et al. A critical review of textile waste recycling: focusing on global policies, recycling approaches, and recovery products application. *Environmental Science and Pollution Research*. 2026. Vol. 33. Iss. 2, p. 366-383. DOI: 10.1007/s11356-025-37335-x

16. Duka A.A., Pashkevich M.A., Sverchkov I.P. Effect of joint thermal utilization of carbonaceous waste and rural refuse on ash fusibility. *Mining Informational and Analytical Bulletin*. 2025. N 9, p. 67-85 (in Russian). DOI: 10.25018/0236_1493_2025_9_0_67

17. Matveeva V.A., Chukaeva M.A., Semenova A.I. Iron ore tailings as a raw material for Fe-Al coagulant production. *Journal of Mining Institute*. 2024. Vol. 267, p. 433-443.

18. Shatrova A.S., Bogdanov A.V., Shkrabo A.I., Alekseeva O.V. Technology for processing waste of the pulp and paper industry into soil ground using natural processes. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*. 2022. Vol. 333. N 8, p. 153-162 (in Russian). DOI: 10.18799/24131830/2022/8/3658

19. Bykova M.V., Malyukhin D.M., Nagornov D.O., Duka A.A. Comprehensive utilization of urban wastewater sludge with production of technogenic soil. *Journal of Mining Institute*. 2024. Vol. 267, p. 453-465.

20. Albuquerque A.R., Gama M.A.P., Lima V.M.N et al. Recycling Nutrients Contained in Biomass Bottom Ash from Industrial Waste to Enhance the Fertility of an Amazonian Acidic Soil. *Agriculture*. 2022. Vol. 12. Iss. 12. N 2093. DOI: 10.3390/agriculture12122093

21. Chiurciu I.A., Dana D., Krogstad T. et al. Waste-based organic fertilizers for improved plant nutrition and yield responses. *Annals of the University of Craiova – Agriculture Montanology Cadastre Series*. 2025. Vol. 55. N 1, p. 238-244. DOI: 10.52846/aamc.v55i1.1684

22. Mikhailov A.V., Piirainen V.Yu., Bobrova E.M., Smirnov A.I. Analysis of the prospects to use peat-based soil conditioners for reclamation of disturbed lands. *Russian Mining Industry*. 2025. N 2, p. 124-130 (in Russian). DOI: 10.30686/1609-9192-2025-2-124-130

23. Choudhary R.C., Singh P.K., Parmar Y.C.J., Lakshmanan A. Novel Developments in Nano Fertilizer for Sustainable Crop Production to Promote Global Food Security. *Sustainability*. 2026. Vol. 18. Iss. 7. N 3198. DOI: 10.3390/su18073198

24. Popov I.O., Pagaleshkin D.A., Fedotov P.S., Kolpakov V.M. The review of avalible technologies for the production of water soluble phosphorus-containing fertilizers. *ChemChemTech*. 2025. Vol. 68. N 5, p. 6-19 (in Russian). DOI: 10.6060/ivkkt.20256805.8f

25. Etesami H., Byoung Ryong Jeong. Silicon (Si): Review and future prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants. *Ecotoxicology and Environmental Safety*. 2018. Vol. 147, p. 881-896. DOI: 10.1016/j.ecoenv.2017.09.063

26. Usman M., Anastopoulos I., Hamid Y., Wakeel A. Recent trends in the use of fly ash for the adsorption of pollutants in contaminated wastewater and soils: Effects on soil quality and plant growth. *Environmental Science and Pollution Research*. 2023. Vol. 30. Iss. 60, p. 124427-124446. DOI: 10.1007/s11356-022-19192-0

27. Matveeva V.A., Smirnov Y.D., Suchkov D.V. Industrial processing of phosphogypsum into organomineral fertilizer. *Environmental Geochemistry and Health*. 2022. Vol. 44. Iss. 5, p. 1605-1618. DOI: 10.1007/s10653-021-00988-x

28. Cherepanova M.V., Lanovetskiy S.V. Evaluation of granulation parameters of pultered fraction of potassium chloride in the presence of lignosulfonate additive. *ChemChemTech*. 2022. Vol. 65. N 6, p. 88-96 (in Russian). DOI: 10.6060/ivkkt.20226506.6591

29. Qingshan Li, Dapeng Zhang, Suzhen Yin et al. Feasibility of Using Animal Manure and Manure-Based Fertilizer as Soil Amendments: Veterinary Drugs Occurrence and Ecological Risk. *Toxics*. 2026. Vol. 14. Iss. 1. N 32. DOI: 10.3390/toxics14010032

30. Barmao V., Wangari G., Orinda B. et al. Comparative Effects of Chicken Manure, Manure Tea, And NPK Fertilizer on The Growth and Yield of Cabbage. *International Journal of Life Science and Agriculture Research*. 2025. Vol. 4. N 10, p. 583-591. DOI: 10.55677/ijlsar/V04I10Y2025-02

31. Romero-Bautista K.J., Palma-López D.J., Vázquez-Navarrete C.J. et al. Assessment of regional substrates and fertilizers for oil palm (*Elaeis guineensis* Jacq.) seedlings production. *Tropical and Subtropical Agroecosystems*. 2025. Vol. 28. N 3. N 158. DOI: 10.56369/tsaes.6367

32. Türk F.N., Arslanoğlu H. Releases of metal bound modified sugar beet pulp (Me^{2+}MSBP) using various aqueous solutions: its use as slow release fertilizer. *Biomass Conversion and Biorefinery*. 2024. Vol. 14. Iss. 9, p. 10671-10685. DOI: 10.1007/s13399-023-04649-0

33. Korovin A.A., Golembovsky V.V., Babenko A.S., Kurovsky A.V. The use of vermicomposting technologies for organic waste disposal. *Tomsk State University Journal of Biology*. 2024. N 68, p. 27-48 (in Russian). DOI: 10.17223/19988591/68/2

34. Manzhina S.A., Rusin L.I. Impact of fertilizers from sewage sludge on agroecological soil indicators. *Land Reclamation and Hydraulic Engineering*. 2025. Vol. 15. N 2, p. 128-148 (in Russian). DOI: 10.31774/2712-9357-2025-15-2-128-148

35. Mmonwuba N.C., Agunwamba J.C., Chisom U. et al. Composting of Cow Dung and Food Waste under Aerobic Conditions for the Improvement of Soil. *Asian Journal of Advanced Research and Reports*. 2024. Vol. 18. Iss. 12, p. 483-492. DOI: 10.9734/ajarr/2024/v18i12845

36. Bykova M.V., Matveeva V.A., Malyukhin D.M. Zayavka na izobretenie N 2026106270 RF. Method for producing organomineral fertilizers. Zayavl. 10.03.2026.

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