ISSN 2411-3336; e-ISSN 2541-9404

JOURNAL OF MINING INSTITUTE
Zapiski Gornogo instituta
Journal homepage: pmi.spmi.ru

Research article
Geotechnical Engineering and Engineering Geology

Ameliorants based on chemical industry waste for the reclamation of mining facilities

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***How to cite this article*:** Patokin D.A., Danilov A.S. Ameliorants based on chemical industry waste for the reclamation of mining facilities. Journal of Mining Institute. 2026. Vol. 281. Iss. 2, p. 146-159.

Abstract
During mining and mineral processing, technogenically disturbed lands are generated and require reclamation. This paper considers the feasibility of producing an effective ameliorant for reclaiming disturbed lands at mining facilities using complex organomineral ameliorants derived from chemical industry waste containing cellulose nitrates. An approach to producing such complex organomineral ameliorants is substantiated. The resulting ameliorants are shown to meet the chemical-composition requirements of GOST R 54534-2011 for use in the technical and biological stages of reclamation and to possess additional beneficial agrochemical properties. In a pot experiment with oat (*Avena sativa*) and meadow bluegrass (*Poa pratensis*), the application of complex organomineral ameliorants produced pronounced positive increases in above-ground plant biomass relative to background models with sand alone: 58.8-104.9 % for oat and 245.5-1721.8 % for meadow bluegrass. Compared with the background model using livestock waste (cattle manure), biomass increases were 5.2-11.6 % for oat and 290.9-413.8 % for meadow bluegrass. A positive effect on the root systems of both species was also observed. The proposed ameliorants based on the waste in question are shown to be suitable for reclamation of mining facilities, and the utilization technology offers a positive economic effect.

Keywords
reclamation of disturbed lands; waste utilization; waste reuse; cellulose nitrates; organomineral ameliorants; chemical destruction; pot experiment

Funding
This work was performed under the State assignment of the Ministry of Science and Higher Education of the Russian Federation (FSRW-2024-0005).

Received: 23.06.2026 ***Accepted: 29.09.2026*** ***Online: 19.10.2026*** ***Published: 30.10.2026***

Introduction

The mining industry is one of the key sectors in Russia's economic structure and holds a leading position in the global economy as well. The provision of national sovereignty of the Russian Federation in the current geopolitical realities largely depends on the effectiveness of this industry.

Operating and decommissioned mining facilities worldwide are sources of complex negative impact on environmental components, which manifests as chemical pollution [1, 2], disruption of structure and integrity [3], accompanied by intensified weathering, which aggravates landscape disturbance [4] and accelerates the formation of technogenic landscapes [5]. These processes are further influenced by geographic factors, such as the location of major mining regions in the boreal zone of the Northern Hemisphere and promising mining areas in the Arctic, which is associated with the extreme instability of northern landscapes to anthropogenic impact [6, 7], as well as the specific features of the natural and technogenic relief of the territory [8].

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According to official data from the Ministry of Natural Resources of Russia, published in the State Report "On the state and protection of the environment of the Russian Federation in 2024", it is precisely technological processes associated with mineral extraction and geological exploration that were primarily responsible for the quantitative and qualitative deterioration of soil fertility and the formation of technogenic relief forms. Thus, in 2017-2024, the total area of disturbed lands amounted to 1148.1 thousand hectares, an increase of 9.7 thousand hectares relative to 2023, while the total area of reclaimed lands by the end of 2024 amounted to 158.1 thousand hectares. There has been a steady annual increase in the area of disturbed lands of industrial designation from 419.4 thousand hectares in 2017 to 508.3 thousand hectares by the end of 2024. To date, the quality of reclamation work and the rate of its implementation remain at a low level [3, 9] and are often associated with high reclamation costs on technogenically disturbed lands and ameliorants [7].

In Russia and globally, the problem of utilizing production and consumption waste remains acute, associated with the growth of industrial production volumes. In Russia alone, according to the State Report "On the state and protection of the environment of the Russian Federation in 2024", from 2014 to 2023 there was an annual increase in the total mass of generated waste from 5168.0 million tons (2014) to 9278.8 million tons (2023), which amounted to 79.5 %. The year 2020 is excluded, as it was associated with the general decline in industrial production during the pandemic. Positive dynamics were noted only for 2024, when the total mass of generated waste decreased to 8515.0 million tons. This is due to minimized waste generation, their use as secondary resources [10] and for reclamation needs, mainly through the introduction of the "by-product" status, which made it possible to transfer part of the waste to a new classification status.

At present, researchers are comprehensively considering a wide range of wastes and sewage sludge that could potentially be used for the reclamation of territories of mining facilities [11, 12]. From a practical standpoint, it is effective to use ash and slag waste from thermal power plants [13], substandard fluxing limestone [12] and ashes of brown coals [11], sludge from soda ash production [14] and iron ore beneficiation waste, sewage sludge at waste disposal sites of loparite and iron ores [15, 16], as well as the combined use of sewage sludge and sediments from biological treatment facilities during the reclamation of a mine water discharge site of a liquidated coal basin [17].

As such wastes, large-tonnage, fire-hazardous wastes from the chemical industry containing cellulose nitrates can be considered, the total mass of which in the territory of the Russian Federation amounts to hundreds of tons and continues to increase with the growth of production. The urgency of the problem arises from the need for an environmentally and economically effective approach to waste utilization. To date, such wastes are either accumulated in the territories of enterprises, where they constitute a source of increased technogenic hazard, or are disposed of by incineration, which is also characterized by significant negative impact on the environment [18-20].

Thus, based on the previous results [18], an approach to the utilization of wastes containing cellulose nitrates to produce mineral soil additives was substantiated; the aim of this study was to assess the potential suitability of complex organomineral ameliorants (OMA) obtained from utilized chemical industry waste for use in the reclamation of disturbed lands.

Materials and methods

The objects of this study, and of the subsequent assessment of their potential suitability for reclaiming disturbed lands, are complex OMA produced from utilized chemical industry waste containing cellulose nitrates, together with livestock waste in the form of cattle manure. The necessary sequential stages in producing the proposed ameliorants are chemical destruction of the main waste component (cellulose nitrates) and mixing of the utilized mass with an organic component.

Chemical industry waste containing cellulose nitrates (nitrocellulose-containing waste, NCCW) consists of sludge formed after mechanical wastewater treatment and is often regarded as waste, since

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it is essentially a substandard process residue sent for neutralization by incineration [21, 22]. NCCW consists of particles with a variable particle-size distribution; qualitatively, it is a mixture of organic (cellulose nitrates, residues of high-molecular-weight organic compounds and plant residues) and mineral parts (calcium and magnesium carbonates, silicon oxides, etc.) [21]. NCCW sampling and primary sample preparation (drying, grinding) were performed as described in [18], which examined the feasibility of their utilization.

To carry out chemical destruction of the waste for subsequent production of complex OMA, the chemical composition of the waste was determined (Table 1). For sample preparation and complete metal extraction, wet digestion with a mixture of nitric acid and hydrogen peroxide (PND F 16.1:2.3:3.11-98) was performed using a Multiwave 3000 microwave digestion system. Analysis was carried out on a Shimadzu ICPE-9000 atomic emission spectrometer and a Shimadzu AA-7000 atomic absorption spectrometer (M-MVI 80-2008). Mercury was determined by PND F 16.2.2:2.3.25-02 using a UKR-1 MTs universal mercury analyzer. Measurement errors were adopted according to the specified methods.

Table 1

Total chemical composition of the waste on an absolutely dry basis

Element	Content, mg/kg	Element	Content, mg/kg
Ca	101317.1±30395.1	Na	251.2±75.7
Al	7398.4±2219.5	Mn	203.5±61.0
Fe	7372.5±2211.7	Zn	148.4±44.5
Mg	3981.5±1194.5	Cr	145.7±43.7
Pb	1590.5±477.2	Ni	58.5±17.6
P	478.1±143.4	As	49.8±14.9
Cu	399.6±119.9	Co	29.7±8.9
K	323.5±97.1	Cd	4.9±1.5
Ti	291.0±87.3	Hg	3.9±0.9

Total nitrogen content in NCCW was 7.3±0.2 wt.% and carbon content was 21.2±0.6 wt.%, as determined on a LECO CHN 628 elemental analyzer.

Chemical destruction of the main component is based on a heterogeneous system using inorganic compounds – strong alkalis and acids [23-25]. To obtain further raw materials for a complex OMA, potassium hydroxide and an aqueous solution of sulfuric acid were selected as the most suitable for destruction. Destruction of NCCW with potassium hydroxide solutions produces the main reaction product, potassium nitrate, which supplies plants with essential mineral nutrients (nitrogen and potassium). This chemical treatment yields a strongly alkaline solution, which was neutralized to pH 6.0-8.0 with orthophosphoric acid, additionally enriching the ameliorant with phosphorus. During destruction with sulfuric acid solutions, the main reaction product is nitric acid; its neutralization with potassium hydroxide to pH 6.0-8.0 also yields potassium nitrate.

At the chemical destruction stage, safe and effective utilization of NCCW is possible, yielding complex mineral soil additives in liquid or solid form [18]. Additives can be used in reclamation only as sources of mineral nutrition for the soil layer being formed, or in the presence of natural soils (including anthropogenically modified ones) that contain organic matter in the humus horizon. Technogenically disturbed mining lands (dumps, production sites and technogenic wastelands), however, are poor in organic matter; the formation of a stable soil-vegetation cover is extremely

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difficult, proceeds slowly, or does not occur at all. Organic matter accelerates the formation of the soil-vegetation complex in reclaimed areas through its positive effect on agrochemical properties (structure, chemical composition, water regime, etc.) [11, 26, 27] and by creating a favorable environment for plants and soil microorganisms [28]. Therefore, the organic component is an important part of the proposed ameliorants.

Peat and sapropel can be used as the organic component of the developed ameliorants. These materials supply substrates with humic substances (up to 50 wt.% in peat), fulvic acids, amino acids and sugars, and contain a full set of nutrients and microelements. They are low-cost and readily available due to significant reserves in the Russian Federation, including in areas where major mining regions and NCCW-producing enterprises are located, especially when used together or with added mineral fertilizers [29, 30]. Other options include sewage sludge from municipal services and cesspool waste, which have rich microflora and elevated contents of total organic carbon and major nutrients (nitrogen, phosphorus, potassium) [7, 27, 31]; livestock waste [32, 33] and sludge-lignin [7, 11].

Despite the variety of organic components available, each option has significant limitations. Peat, whose organic matter is resistant to microbial decomposition due to the acidic reaction of the medium, can slow the mineralization of organic nitrogen and requires biological preparations; moreover, preliminary neutralization is necessary to prevent acidification of the resulting soil substrate. Humic substances are converted into water-soluble forms available to plants by additional chemical or mechanical treatment [29]. The use of these components is also limited by the need for preliminary preparation (dewatering), which reduces their effectiveness, by strong variability in component composition, and by small extraction volumes and the scattered geography of deposits [34].

Sewage sludge from municipal and domestic services and cesspool waste require preliminary preparation, have inconsistent chemical compositions, and, like sludge-lignin [11], may contain elevated concentrations of heavy metals (HM). Given the elevated HM contents in NCCW after chemical destruction, this limits their use for producing an organomineral ameliorant.

The limiting factors for manure use are the strict requirement for total nitrogen dosage to avoid the harmful effect of the ammonium form and compliance with sanitary requirements. An additional factor is the heterogeneous chemical composition caused by differences in diet and breed composition [33]. However, despite these disadvantages, the main advantages are availability, a positive synergistic effect when used with mineral fertilizers, and maintenance of a stable organic carbon level [32].

After evaluating the advantages and disadvantages of the potential organic components for the complex OMA, livestock waste was selected. Litter-free cattle manure was used as the organic component. It was sampled at an agricultural enterprise in accordance with GOST 26712-85 and, according to the enterprise's documentation, met the toxicological, veterinary-sanitary and hygienic requirements of GOST 33830-2016; therefore, these indicators were not determined in this study. For subsequent OMA production and to set up a pot experiment assessing its effectiveness, the following manure characteristics were determined: moisture content 63.1±0.8 wt.% (GOST 26713-85); organic matter content on an absolutely dry basis 34.5±0.5 wt.% (GOST 27980-88); and nitrogen content recalculated to an absolutely dry basis 1.3±0.1 wt.% (LECO CNH-628S elemental analyzer; errors taken from technical documentation).

When designing the ameliorant compositions, the total organic carbon to total nitrogen (C:N) ratio was taken into account, as it largely controls the formation of the soil-vegetation complex. According to various estimates, this ratio ranges from 11 to 17 for natural soils [35], while the optimum

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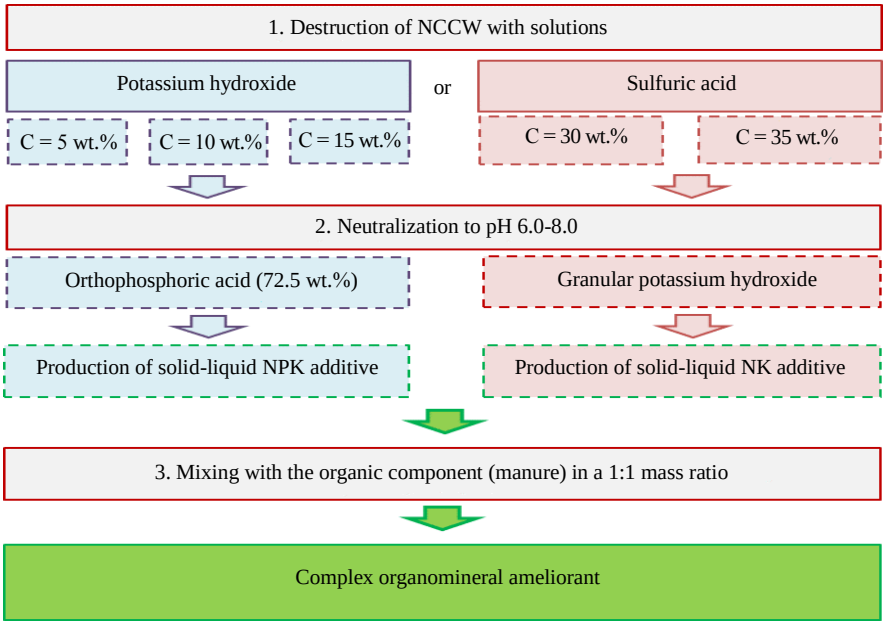


Fig.1. Scheme for producing a complex organomineral ameliorant

for soil microorganisms is 20±4 (with an average range from 2 to 24) or not less than 20-25 during composting [36]. Thus, according to the calculations performed, the minimum threshold of 11:1 was met when mixing utilized NCCW and manure in a 1:1 ratio.

The complex OMA was produced according to the scheme in Fig.1. The OMA compositions were named after the reagent used for chemical destruction of NCCW and its concentration.

To justify the applicability of GOST R 54534-2011 "Resource Conservation. Sewage Sludge. Requirements for Use in the Reclamation of Disturbed Lands" to each of the five ameliorant compositions, the hazard class was first determined by biotesting. This GOST is applicable because NCCW is a type of sewage sludge.

Biotesting was performed according to PND F T 14.1:2:3:4.10-04 using the alga *Chlorella vulgaris* Beijer at dilution factors of 1; 10; 100; 1000 and 10,000, with KV-05 and KVM-05 cultivators and an IPS-03 photoelectric colorimeter. These dilution factors were chosen because the ameliorants are based on livestock waste and utilized NCCW. At a dilution factor of 1, the aqueous extracts were colored. To eliminate this interference when measuring the optical density of the suspension after algal cultivation, a correction was applied by first measuring the optical density of the OMA aqueous extract kept under the same conditions but without the Chlorella culture.

Next, sample preparation and determination of agrochemical and toxicological parameters of the obtained complex OMA were performed, and the results were compared with the requirements of GOST R 54534-2011. Mass fractions of dry matter and ash were determined according to GOST 26713-85 and GOST 26714-85 using a LECO TGA 701 thermogravimetric analyzer (errors taken from the equipment's metrological characteristics). Chemical oxygen demand (COD) was determined by PND F 14.1:2:4.210-2005 on a Hach-Lange DR1900 spectrophotometer using the photometric method for salt extracts (GOST 26483-85). Five-day biochemical oxygen demand (BOD_5) was calculated according to RD-APK 1.10.15.02-17 for litter-free manure from the obtained COD values.

Sample preparation and determination of gross contents of elements (Cr, Pb, Cd, Ni, Cu, Zn), total phosphorus, total potassium and total nitrogen were performed as described for the gross chemical composition of NCCW. Organic matter recalculated to carbon was determined by the thermogravimetric method according to GOST 27980-88 using a LECO TGA 701 analyzer.

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The effectiveness of the proposed ameliorants was assessed in a pot experiment with soil cultures to determine plant mineral nutrition under strictly controlled conditions (two replicates) [37]. The substrate was construction sand washed with tap water and then distilled water, dried at 105 °C, with a fraction of 2.2 mm, sieved through a 2.0 mm sieve.

Oat (*Avena sativa*) and meadow bluegrass (*Poa pratensis*) were selected as test plants to assess ameliorant effectiveness (a pot experiment requires at least two plant species). The choice of meadow bluegrass is justified by its recommended use in reclamation of disturbed lands (GOST R 57446-2017) in the boreal zone, where most mining regions and the chemical enterprises in question are located. Oat was chosen because of its proven effectiveness and successful use in soil reclamation and phytoremediation. In addition, oat is a classic species for pot experiments due to its pronounced response to agrochemicals, significant above-ground biomass increase and short growing season [37, 38].

The potential use of oat at reclaimed mining facilities can expand the raw material base of the chemical enterprises in question, which is linked to the development of high-quality industrial cellulose nitrates from alternative cellulose-containing raw materials such as oat [38, 39]. This approach enables a closed cycle of cellulose nitrate production, in which waste from the main process is utilized as a raw material for ameliorants. When these ameliorants are used to reclaim disturbed mining lands with oat, they reduce the technogenic load, help return lands to economic use and replenish the chemical industry's raw material base.

Plants were grown in opaque plastic pots with perforated bottoms, volume 6.3 dm^3, height 0.2 m, surface area 0.03 m^2, following standard requirements for pot experiments [37] to ensure normal root and shoot development.

Ameliorant application doses, corrected for moisture, were calculated for KOH5 and KOH10 from chemical analysis data showing lead contents 1.1-1.5 times above the norms; for the other compositions, the minimum dose was based on a total nitrogen content of 120 kg/ha. Ameliorant doses per pot: KOH5 – 50.4; KOH10 – 58.0; KOH15 – 99.3; $H_2SO_4$30 – 51.9; $H_2SO_4$35 – 71.0 g.

The controls were pots with sand only, without ameliorants (absolute control), and pots with sand plus cattle manure at 120 kg/ha based on total nitrogen (relative control).

The number of seeds was chosen according to the pot volume; the experiment used a monoculture, with only one species sown per pot [37]. Fifty seeds of *Avena sativa* were sown per pot and thinned to 20 on day 14 and to 15 on day 28. *Poa pratensis* was sown at 100 seeds per pot and thinned to 50 on day 14. The pot experiment was conducted in NL79-03-04 LD phytostands under a photoperiod 16h, 13,000 lx illumination, 20 °C, substrate moisture at 60 wt.% of the full moisture capacity of the sand (GOST 12038-84), and watering with settled tap water. The experiment start date was the day when 50 % of seeds had emerged, following the standard approach for pot experiments, in which mass emergence marks the beginning of active growth and ensures uniform conditions for all plants. For *Avena sativa*, this first control point is established by GOST R ISO 22030-2009.

The oat experiment lasted 61 days; above-ground biomass increase was assessed on days 14, 28 and the final day 61 (Fig.2), with control points chosen by analogy with GOST R ISO 22030-2009. The meadow bluegrass experiment lasted 81 days; because of the small above-ground biomass increase, assessment was performed only on day 14 and the final day 81 (Fig.2), selected according to plant growth phases.

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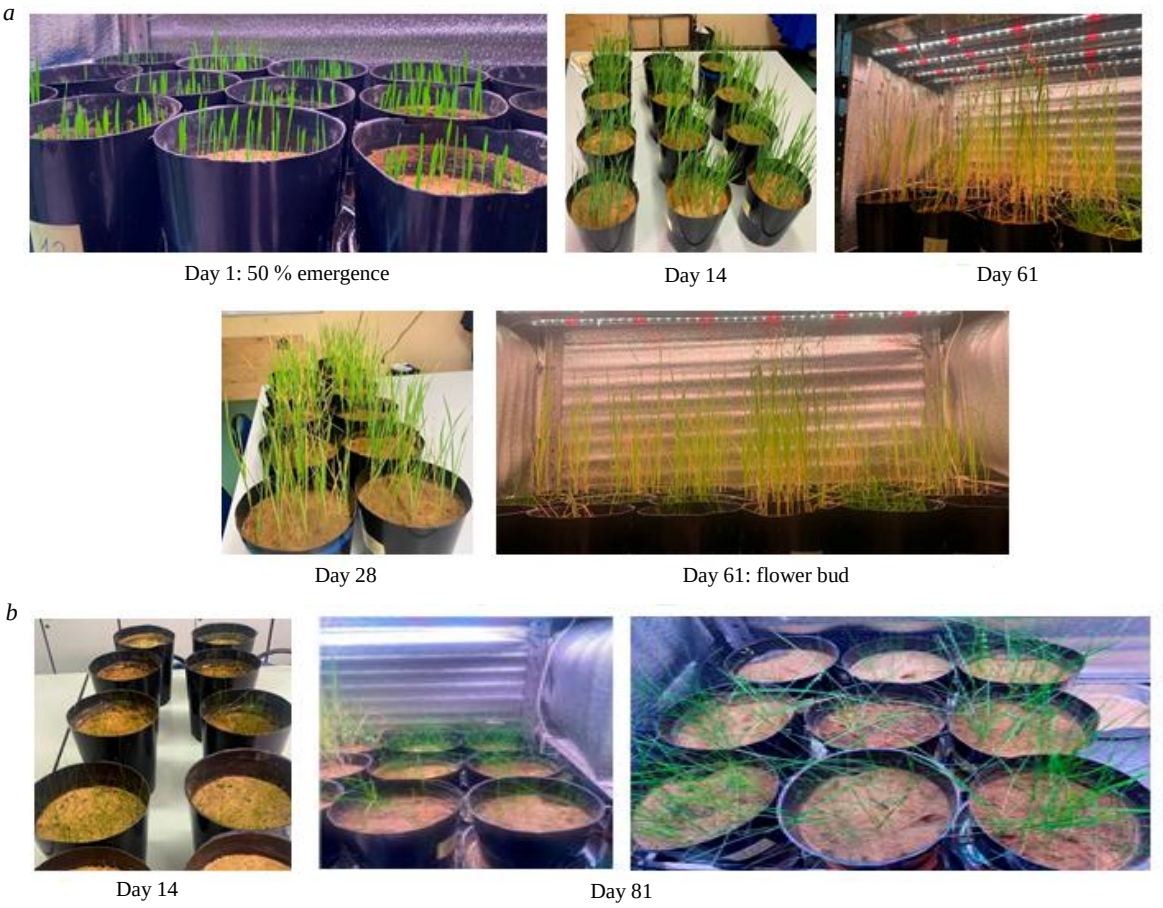


Fig.2. Stages of the pot experiment with oat (*Avena sativa*) (*a*) and meadow bluegrass (*Poa pratensis*) (*b*)

Above-ground biomass increase was assessed by cutting plants 2 cm above the upper lateral root, drying at 60-70 °C to air-dry state and then at 105 °C to absolutely dry state, and weighing. Seed germination was also determined according to GOST 12038-84.

At the end of the pot experiment, roots were washed from the pots by the classical Savvinov method. Root biomass increase was assessed by determining root mass and volume and calculating root saturation (root volume to total pot volume) for each pot using classical methods [40-42].

In addition, the contents of nutrients (total potassium, total phosphorus, magnesium and calcium) and possible bioconcentration of heavy metals and arsenic in gross forms (As, Co, Cr, Cd, Cu, Ni, Pb, Zn) were assessed in above-ground biomass. Plant material from the pots was preliminarily dried at 60-70 °C in a LOIP LF-60/350-VS-2 drying oven and then ground in a ball mill with tungsten carbide grinding bodies. The moisture content of the dried samples was then determined to recalculate concentrations to an absolutely dry basis. Samples were mineralized using a Multiwave 3000 microwave digestion system with the plant-sample decomposition program; analysis was performed on a Shimadzu ICPE-9000 atomic emission spectrometer and a Shimadzu AA-7000 atomic absorption spectrometer according to M-MVI 80-2008.

Results discussion

Based on the obtained toxic dilution factors (TDF) of aqueous extracts of the ameliorants (KOH5 – 3, KOH10 – 3, KOH15 – 4, $H_2SO_4$30 – 3, $H_2SO_4$35 – 3), and in accordance with Order N 158 of the Ministry of Natural Resources of Russia dated 31.03.2025, hazard class IV for the environment was established for each composition, which fully satisfies the requirements of GOST R 54534-2011.

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The agrochemical and toxicological parameters of the obtained complex OMA, determined in accordance with GOST R 54534-2011, are presented in Table 2; additional beneficial agrochemical characteristics are given in Table 3. Bacteriological parameters were not determined, in accordance with the documentation for the manure.

Table 2

Characteristics of the obtained complex OMA compared with GOST R 54534-2011

GOST R 54534-2011			KOH5	KOH10	KOH15	$H_2SO_4$30	$H_2SO_4$35
Parameter	Technical stage	Biological stage					
Dry matter, %	45.0	< 35.0	28.8±0.7	27.9±0.7	25.8±0.7	34.4±0.7	29.3±0.7
Ash content, %	65.0	< 65.0-85.0	40.1±0.7	46.1±0.7	55.3±0.7	58.3±0.7	59.3±0.7
Total nitrogen, %	–	< 0.5	2.6±0.1	2.3±0.1	1.5±0.1	2.9±0.1	2.8±0.1
Total phosphorus, %	–	< 1.5	1.3±0.4	2.2±0.6	5.5±1.6	1.5±0.5	1.5±0.5
pH of salt extract	5.0-8.5		7.5±0.1	7.7±0.1	8.3±0.1	7.4±0.1	7.1±0.1
Mercury, mg/kg	> 30.0	> 15.0	<0.02				
Chromium, mg/kg	> 2000.0	> 1000.0	45.3±13.6	43.9±13.2	35.4±10.6	20.8±6.2	17.4±5.2
Lead, mg/kg	> 1000.0	> 500.0	698.6±209.6	579.1±173.7	466.4±139.9	231.8±69.5	185.8±55.7
Cadmium, mg/kg	> 60.0	> 30.0	0.4±0.1	0.3±0.1	0.2±0.1	2.9±0.9	2.8±0.9
Nickel, mg/kg	> 800.0	> 400.0	22.1±6.6	18.7±5.6	15.7±4.7	9.9±2.9	9.1±2.7
Copper, mg/kg	> 1500.0	> 750.0	213.8±64.2	175.7±52.7	141.8±42.5	75.6±22.8	69.6±20.9
Zinc, mg/kg	> 7000.0	> 3500.0	181.4±54.4	151.3±45.4	132.4±39.7	100.7±30.2	102.9±30.9
Arsenic, mg/kg	> 40.0	> 20.0	1.3±0.4	1.3±0.4	1.4±0.4	6.9±2.1	5.00±1.5
COD, mg/dm^3	> 700.0	> 700.0	429±86	387±77	323±65	295±59	302±60
BOD_5, mg O_2/dm^3	> 500.0	> 500.0	51±10	46±9	39±8	35±7	36±7

Note. Green – compliance with requirements; yellow – within measurement error; pink – non-compliance with requirements.

Table 3

Agrochemical characteristics of the obtained complex OMA

Agrochemical parameter	KOH5	KOH10	KOH15	$H_2SO_4$30	$H_2SO_4$35
Total K content, %	7.4±2.2	12.1±3.6	15.9±4.8	14.3±4.3	13.7±4.1
Total organic carbon content, %	29.9±0.7	26.9±0.7	22.4±0.7	20.4±0.7	20.8±0.7
C:N ratio	11.5	11.7	14.9	13.9	13.6
Ca content, %	4.2±1.3	3.4±1.0	3.1±0.9	2.7±0.8	2.6±0.8

A comparison of the chemical composition of the complex OMA with the requirements of GOST R 54534-2011 for reclamation shows (see Table 2) that the obtained compositions fully meet the requirements of the GOST, except for the mass fractions of dry matter and ash, which can be corrected by adding an inert material. The elevated lead content in KOH5 and KOH10 can also be reduced by adding an inert material. Additional determination of bacteriological parameters is necessary regardless of the documentation for the manure used to produce the OMA.

The determined agrochemical parameters (Table 3), for which GOST R 54534-2011 imposes no requirements, are beneficial characteristics of the complex OMA compositions, since the ameliorants additionally contain potassium and calcium, which are important plant nutrients.

The C:N ratios calculated from the chemical composition of the ameliorants are above the optimal range (at least 11:1), while the average optimum for soil microorganisms of 20±4 can be reached after the first growing season through the formation of herbaceous plant litter and additional total organic carbon input, as confirmed by [35].

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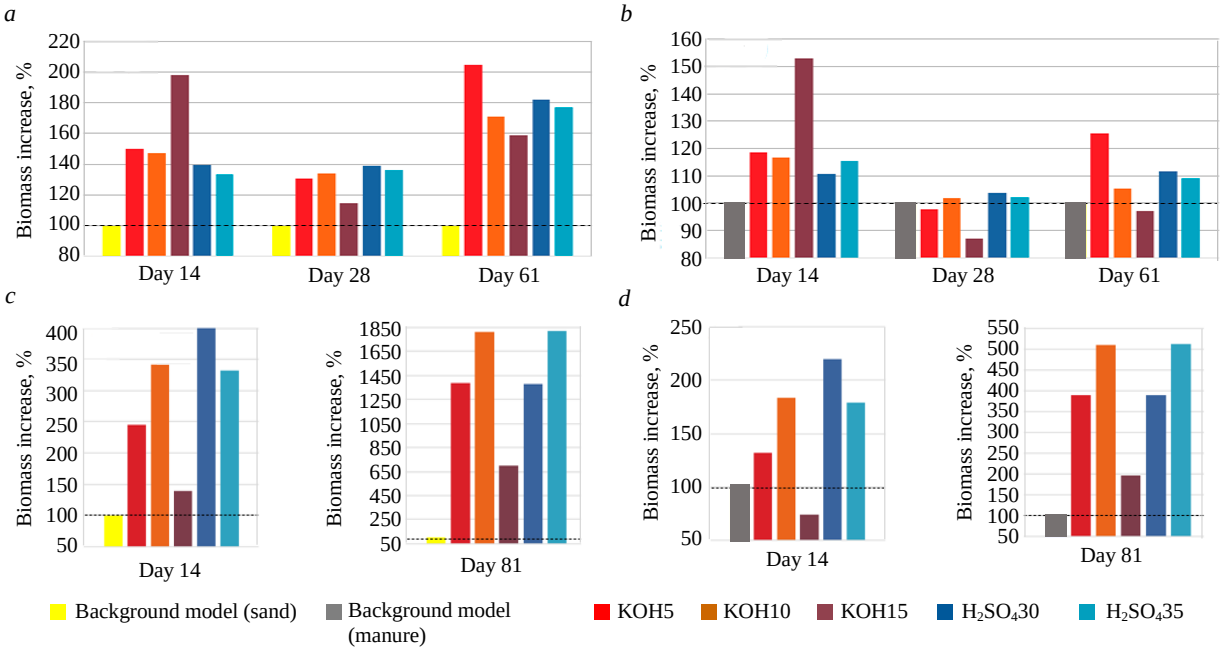


Fig.3. Increase in above-ground biomass of oat (*Avena sativa*) and meadow bluegrass (*Poa pratensis*) over the background model with sand (*a*, *c*) and with manure (*b*, *d*)

The results of the pot experiment assessing above-ground biomass increase on an absolutely dry basis compared with background models of soil-vegetation complexes are shown in Fig.3.

Thus, a pronounced positive effect relative to the absolute control can be concluded at the end of the experiment: the final relative biomass increase was 58.8-104.9 % for oat and 245.5-1721.8 % for meadow bluegrass. Relative to the relative control, all compositions except KOH15 showed a positive effect. Biomass increase was 5.2-11.6 % for oat and 290.9-413.8 % for meadow bluegrass.

On day 14 of the experiment, OMA KOH15 showed the highest results, which is associated with excessive potassium supply during the initial growing period; subsequently, however, potassium began to exert a toxic effect on the plants. This is confirmed by analysis of the above-ground biomass of both plant species for potassium, phosphorus, calcium, and magnesium, which showed excessive potassium accumulation in plant biomass after application of KOH15, accompanied by a sharp drop in calcium and magnesium contents, indicating a toxic effect. This result indicates the need to repeat the experiment with KOH15, adjusting the application dose according to this parameter rather than total nitrogen. Meadow bluegrass showed the greatest positive effect on above-ground biomass increase, which makes it preferable for reclamation of disturbed lands using the obtained OMA, both as a monoculture and in grass mixtures.

The assessment of seedling numbers and total germination (Table 4) shows no acute phytotoxicity, and the average germination for each experimental variant with both plant species indicates a slight but positive effect exceeding germination in the background models.

The results of the root biomass assessment (Fig.4, Table 5) show a pronounced positive effect from the ameliorants in each pot, except for KOH15 (Fig.4) with meadow bluegrass, which is likewise associated with excessive total potassium in the OMA and the need to adjust the application dose for KOH15 based on the nutrient content. The increase in root biomass was 96.1-207.9 % for oat and 42.3-599.5 % for meadow bluegrass relative to the sand-only background model. Relative to the manure background model, the increase was 1-58.6 % for oat and 32.9-444.6 % for meadow bluegrass. For both plant species, KOH5 and KOH10 showed lower efficiency than $H_2SO_4$30 and $H_2SO_4$35.

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A more pronounced positive effect on root biomass increase from the ameliorants was observed for meadow bluegrass. Taking into account both above-ground and root biomass increases, preference should be given to KOH5 or $H_2SO_4$30 and $H_2SO_4$35.

Table 4

Results of seed germination assessment in the pot experiment

Pot	*Avena sativa*			*Poa pratensis*		
	Number of seedlings	Germination, %	Average germination, %	Number of seedlings	Germination, %	Average germination, %
Background model (sand)	40 45	80 90	85±10	59 48	59 48	54±14*
Background model (manure)	43 45	86 90	88±9	61 53	61 53	57±14
KOH5	46 46	92 92	92±8	56 62	56 62	59±14
KOH10	48 46	96 92	94±7	58 64	58 64	61±14
KOH15	40 45	80 90	85±10	63 51	63 51	57±14
$H_2SO_4$30	47 46	94 92	93±7	60 57	60 57	59±14
$H_2SO_4$35	46 45	92 90	91±8	59 55	59 55	57±14

*Adopted according to GOST 12038-84; the pots were divided into two equal parts, and the sample comprised 4×50 seeds at a sowing rate of 100 seeds per pot.

Determination of root volume and root saturation in addition to root mass increase allows the availability of nutrients to roots and their development in forming soil-vegetation complex to be assessed. The results of the pot experiment (Table 5) indicate positive dynamics in both control variants. The negative results for meadow bluegrass with KOH15 are expected but also require a repeat experiment.

Assessment of heavy metal and arsenic bioconcentration in above-ground phytomass by comparing the established gross contents with the MPC (APC) for sandy substrates and regional background contents adopted as in [18] showed no accumulation of toxic elements in any experimental variant. A positive result was also obtained for the KOH5 and KOH10 variants, which had elevated lead contents. When OMA doses are applied based on total nitrogen content, the ameliorants can be considered environmentally safe.

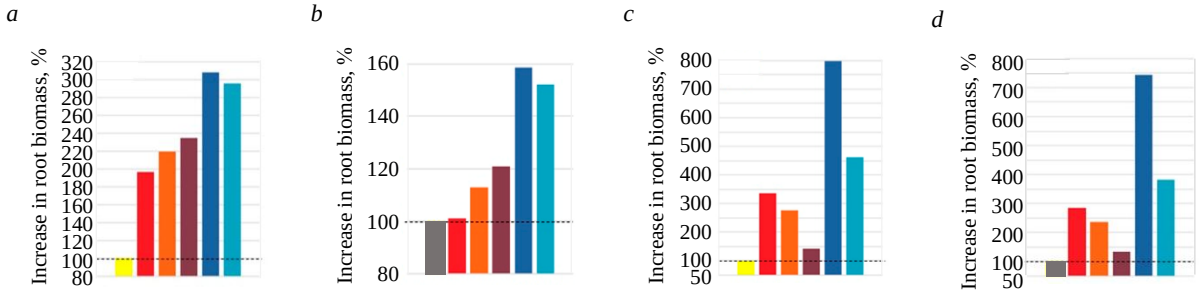


Fig.4. Increase in root biomass of oat (*Avena sativa*) and meadow bluegrass (*Poa pratensis*) over the background model with sand (*a*, *c*) and with manure (*b*, *d*).
For legend, see Fig.3

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Table 5

Estimated root parameters for each experimental variant

Experimental variant	*Avena sativa*		*Poa pratensis*	
	Root volume, cm^3	Root saturation, %	Root volume, cm^3	Root saturation, %
Absolute control	12.0	0.21	6.0	0.11
Relative control	17.5	0.31	7.0	0.12
KOH5	18.5	0.33	11.5	0.21
KOH10	21.5	0.38	9.5	0.17
KOH15	22.0	0.38	3.5	0.06
$H_2SO_4$30	26.0	0.46	17.0	0.30
$H_2SO_4$35	24.0	0.43	13.0	0.23

Given the positive experimental results, an ecological and economic assessment of the proposed NCCW utilization method with OMA production was carried out per 1 t of utilized waste, along with a calculation based on data from a chemical industry enterprise where 3300 t of NCCW are accumulated. Economic calculations were not performed for the KOH15 composition.

The calculation was based on NCCW utilization costs and on the reduction of fees for negative environmental impact from incineration followed by ash disposal at waste disposal sites, both for the enterprise's own needs and for sale of the finished commercial product.

The general technological scheme of utilization comprises the following operations:

• preparation of the destructor solution in a 2.5 m^3 vertical mixer;

• feeding of averaged NCCW batches by an inclined screw feeder into a 3.0 m^3 vertical mixer;

• feeding of the destructor solution into the vertical mixer loaded with NCCW and destruction for 30-60 min (depending on the selected reagent);

• neutralization of the reaction mass in the vertical mixer (destruction and neutralization are carried out in the same apparatus);

• feeding of the neutralized reaction mass into the soil mixer;

• loading of manure into the soil mixer for homogenization in a 1:1 ratio (on an absolutely dry basis) relative to the mass of NCCW fed for utilization;

• unloading of the complex OMA to a storage site for natural drying.

The yield of commercial product, taking into account the natural moisture of the finished substrate, is 10 t per 1 t of NCCW utilized. The batch size of NCCW fed for utilization is 500 kg, which is determined by the maximum size of commercially available domestic soil mixers, without additional design and manufacturing costs. The approximate capital investment in equipment was 2.5 million rub. Operating costs, including material costs (electricity, reagents and manure), labor remuneration, insurance contributions, depreciation, and other costs, amounted to 230.0-265.8 thousand rub. per 1 t of NCCW, depending on the selected reagent. Thus, given the production of 10 t of OMA per 1 t of NCCW utilized and a 10 % markup, the estimated price of the complex OMA was 25,300-29,200 rub., depending on the selected reagent.

The fee calculation was based on the legislative prohibition of open-air incineration with a multiplying factor of 100 (the enterprises in question where NCCW is generated are currently classified as category I negative environmental impact facilities), using the quantitative composition of emissions generated during NCCW incineration. Incineration of 1 t of NCCW entails a fee of 6238 rub.; for one industry enterprise where 3300 t of NCCW are accumulated, the fee is 20.6 million rub. Given the formation of 93.2 kg of ash per 1 t of NCCW incinerated, the disposal fee within the limits, according to Decree of the Government of the Russian Federation N 881 dated 31.05.2023 “On approval of the Rules for calculating and collecting fees for negative impact on the environment”, will

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be 2654 rub. and 816,626 rub., respectively. The damage to atmospheric air, calculated according to Order N 59 of the Ministry of Natural Resources and Ecology of the Russian Federation dated January 28, 2021 "On approval of the Methodology for calculating the amount of harm caused to atmospheric air as a component of the natural environment", amounted to 21,813 rub. for incineration of 1 t of NCCW and 72 million rub. for 3300 t.

A calculation of investment attractiveness for an industry enterprise (with 3300 t to be utilized) showed that the capital investment in the proposed technology is recovered within the first year, even without taking into account sales of the commercial product. To recover the capital investment, at least 59 t of NCCW must be utilized. Given the capacity of the selected equipment, equal to 9 t of NCCW per day, 3300 t can be utilized within one calendar year, taking into account the enterprise's existing operating mode.

Conclusion

The results of this study demonstrate the high potential of complex organomineral ameliorants produced by chemical destruction of cellulose nitrate-containing waste followed by mixing with manure in a 1:1 mass ratio. The resulting complex OMA fully comply with the agrochemical and toxicological requirements of GOST R 54534-2011, except for dry matter and ash content, which can be corrected by adding an inert material. In addition, the OMA contain potassium and calcium.

The results of the pot experiment with oat (*Avena sativa*) and meadow bluegrass (*Poa pratensis*) indicate that the developed OMA have high potential for use during the biological stage of reclamation. This is further supported by the use of plant species most in demand for reclamation and for assessing the potential of agrochemicals. All compositions except KOH15 produced a pronounced increase in both above-ground and root biomass compared with the two background models (sand and manure). Notably, the best results were obtained with the complex OMA KOH5, $H_2SO_4$30 and $H_2SO_4$35. No phytotoxicity was observed throughout the pot experiment for all compositions except KOH15; for KOH15, additional phytotoxicity testing is required.

The ecological and economic assessment demonstrates the environmental and economic feasibility of the proposed utilization method, supported by a positive environmental effect that eliminates atmospheric emissions and reduces the technogenic hazard from NCCW. The interaction between the chemical and mining industries considered in previous works is confirmed, whereby chemical production waste serves as a raw material for producing ameliorants used in the reclamation of mining facilities.

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The authors declare no conflict of interests.

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