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Article

Ecological and chemical properties of soils on self-revegetating coal dumps in the forest-steppe zone of Western Siberia

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Abstract. Soils and vegetation were examined on self-revegetating coal mining dumps in the Kuznetsk Basin (Kuzbass) during the 2024–2025 field seasons. Four soil types representing various stages of pedogenesis were identified: initial embryozems, organo-accumulative embryozems, soddy embryozems, and humus-accumulative embryozems. Morphological descriptions were complemented by analyses of particle-size distribution, actual and exchangeable acidity, organic matter content, catalase and urease activity, and trace element composition. The total pollution index (Zc) and geo-accumulation index (Igeo) were calculated. The fine-earth fraction predominated in all embryozems except the initial stage. Bulk density and alkalinity decreased with the progression of plant community development. Elevated organic matter content in the embryozems was attributed to the incorporation of coal particles. Both catalase and urease activity increased with advancing pedogenesis. Based on Zc values, the surface layer (0–10 cm) of the embryozems fell within the permissible pollution range. The Igeo values indicated slight contamination with lead, copper, and nickel, and strong contamination with arsenic.

Keywords: coal mining, embryozems, vegetation, enzymes, heavy metals, geo-accumulation index

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Научная статья

Эколого-химические свойства почв на самозарастающих угольных отвалах лесостепной зоны Западной Сибири

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Аннотация. Изучены почвы и растительность отвалов угледобычи Кузбасского угольного бассейна, оставленные под самозарастание. Исследование проведено в 2024–2025 гг. На отвалах диагностированы 4 типа почв, представляющих различные стадии почвообразования: эмбриоземы инициальный, органо-аккумулятивный, дерновый и гумусово-аккумулятивный. Проведено морфологическое описание почв, изучен их фракционный состав, актуальная и обменная кислотность, содержание органического вещества, активность каталазы и уреазы, микроэлементный состав. Рассчитан суммарный показатель загрязнения (Zс) и индекс геологического накопления элементов в почвах (Igeo). Выявлено преобладание фракции мелкозема во всех типах эмбриоземов, кроме инициального. Отмечено снижение плотности и щелочности исследуемых почв с развитием растительной группировки. Наблюдалось высокое содержание органического вещества в эмбриоземах из-за включения углистых частиц. Активность каталазы и уреазы увеличивалась по мере развития почвы. Согласно величине Zс, поверхностные слои (0–10 см) эмбриоземов характеризуются допустимым уровнем загрязнения. Igeo показал слабое загрязнение почв свинцом, медью и никелем, а также сильное загрязнение мышьяком.

Ключевые слова: угледобыча, эмбриоземы, растительность, ферменты, тяжелые металлы, индекс геоаккумуляции

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Introduction

Coal mining exerts considerable pressure on the environment (Akulov, 2014; Ismailov et al., 2023; Merkuryev et al., 2021). As coal remains one of the most widely used energy sources (Singh and Narzary, 2021), extraction rates continue to increase annually. Mining operations entail the removal of land for open pits and waste storage facilities – mine dumps (Bragina, 2016) – as well as the destruction of the soil cover and contamination of soils (Zinovieva et al., 2020). The expansion of dump areas characterized by low biological diversity contributes to the destabilization of the environment (Копытов and Kupriyanov, 2019). Moreover, the spontaneous combustion of coal dumps has been shown to elevate atmospheric concentrations of polycyclic aromatic hydrocarbons (Nadudvari et al., 2021).

Mitigating the negative impact of coal mining dumps is impossible without reclamation of disturbed lands, which involves the restoration of soil and vegetation cover. In China, even a monodominant plant community used for the reclamation of coal dumps has been shown to improve soil properties (Yuan et al., 2018). The vegetation of reclaimed dumps is characterized by distinct vertical stratification and a diverse floristic composition (Kalinina and Germonova, 2018).

Soil microorganisms are among the first to respond to deteriorating environmental conditions (Terekhova, 2007). Accordingly, the activity of soil microbiota serves as an integral parameter for assessing the recovery of soil and vegetation cover. Soil enzyme activity is directly involved in redox processes and the transformation of carbon and nitrogen, and thus reflects the functional state of soil microorganisms (Novoselova and Tukhvatullina, 2009). A decline in enzymatic and microbial activity can be considered an early diagnostic indicator of adverse impacts on the soil (Wander, 2009).

In Kuzbass, coal mining operations bring vast quantities of overburden and host rocks to the surface, which subsequently become parent materials for soil formation. These rocks consist of a heterogeneous mixture of sandstone, mudstone, siltstone, and mantle loams (Gossen and Belanov, 2011). The dump rocks, particularly those of the Listvyansky coal mine, are non-toxic, which facilitates the natural recovery of soil and vegetation cover (Boguslavskiy et al., 2021). The composition and properties of dump materials, along with climatic conditions and site-specific ecological characteristics, directly influence the content and distribution of trace elements through mobilization and inputs via surface runoff and atmospheric transport. Kolpakova et al. (2024) reported data on the chemical composition of soils from the dump of the Barzas open-pit mine, located in the same natural zone (forest-steppe) as the Listvyansky mine. Samples from the Barzas dump contained substantial amounts of carbon, strontium zirconate, calcium carbonate, cobalt selenate, and molybdenum nitride. Studies of soils from the Korchakolsky coal mine in Kemerovo Region revealed contamination with zinc, copper, nickel, and arsenic (Vorobyeva et al., 2023); moreover, an inverse correlation was found between the concentrations of these elements and enzymatic activity. In the soils of reclaimed dumps of the Kizel coal basin, trace element concentrations increase with depth, which is attributed to rising soil acidity caused by sulfide minerals present in the overburden. Elevated levels of lithium, boron, iron, lead, arsenic, and selenium relative to background values have also been reported (Perevoshchikova et al., 2023).

The aim of this study was to examine the properties of embryozems and to identify the stages of their development on self-revegetating coal dumps in the forest-steppe zone of Kuzbass. To achieve this goal, the morphological and physical properties of the soils were described, their acidity and organic matter content were characterized, and the ecological and geochemical status of the soils was assessed.

Materials and methods

Description of the study area

The Kuznetsk Coal Basin (Kuzbass) is located in Kemerovo Region, in central Eurasia, within a zone of sharply continental climate characterized by pronounced and persistent seasonal fluctuations in air temperature (Kurachev and Androkhanov, 2002). The study area lies at the boundary between the Kuznetsk Depression and Gornaya Shoria. Kuzbass is situated in the central part of the Eurasian plate. A considerable portion of the region belongs to the Altai–Sayan folded area, while its northeastern part extends into the West Siberian Platform (Udodov, 2017).

Open-pit coal mining in Kuzbass is carried out at deposits that primarily extract sediments of the Balakhonskaya (C₂₋₃ – P₁) and Kolchuginskaya (P₂) series (coal-bearing formations), represented by interbedded coal seams, sandstones, siltstones, and mudstones of varying thickness (Kutepov et al., 2021). The Kuznetsk Coal Basin is a large synclorium that originated in the Middle Paleozoic (Devonian) and underwent its main development in the Late Paleozoic (Carboniferous – Permian) (Udodov, 2017).

The study area belongs to the Mariinsk-Achinsk Soil District, which encompasses a dissected forest-steppe and pre-mountain forest-steppe with variable degrees of forest cover. Moisture conditions are optimal throughout the year (400–500 mm), and drainage is well-developed, which precludes the formation of hydromorphic soils. According to the dendrological zoning of Yu.P. Khonov (1979), the study area falls within the South Kuznetsk district of pine and broadleaf species.

The parent materials are represented by calcareous, light brown, and brownish-yellow loess-like clayey-silty heavy loams or silty-clayey light clays. The soils of the study area are gray forest soils, as well as leached and podzolized chernozems (Trofimov, 1975). Soddy-podzolic soils are found beneath coniferous–broadleaf forests, meadow soils occupy depressions, and underdeveloped chernozem-like stony soils occur on hilltops (Belanov et al., 2013).

Study focus

The study focused on soils in self-revegetating and reclaimed areas planted with forest vegetation on leveled dumps of the Listvyansky coal mine (Novokuznetsk District, with the nearby Mikhaylovka village located 1 km to the west). The deposit is now depleted. The soil cover was examined on two dumps, aged 10 and 40 years. In both cases, the dump surfaces are occupied by embryozems. Vegetation exhibits a mosaic pattern across the dumps and includes both herbaceous and tree-shrub plant communities, with some areas entirely devoid of plant cover.

Research methods

Fieldwork was conducted during the summer of 2024, and laboratory processing was carried out in 2024–2025. Soil samples were collected from three dumps of different ages. Sampling was performed along three walls of shallow pits, layer by layer, from depths of 0–5 cm, 5–10 cm, and 10–20 cm. The following analyses were performed on the soil samples: actual acidity (pH of water extract)¹ and exchangeable acidity (pH in 3 M KCl solution)². Particle-size distribution was determined by the sieve method³. Organic matter content was measured using the Tyurin method with photometric endpoint determination⁴. Catalase activity (CA) was determined using the permanganate method of Johnson and Temple (Khaziev, 1990), and urease activity (UA) was determined by the colorimetric method (Khaziev, 1990). Trace element composition was analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AES) using Elan 900⁵. All chemical analyses for organic matter, enzyme activity, and trace elements were performed in triplicate (three biological replicates).

¹ GOST 26423–85. Soils. Methods for determination of specific electric conductivity, pH and solid residue of water extract.

² GOST 26483–85. Soils. Preparations of salt extract and determination of its pH by CINA method.

³ GOST 12536–2014. Soils. Methods of laboratory granulometric (grain-size) and microaggregate distribution.

⁴ GOST 26213–2021. Soils. Methods for determination of organic matter.

⁵ GOST ISO 22036–2014. Soil quality. Determination of trace elements in extracts of soil by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

For the ecological and geochemical assessment of surface soil layers, the total pollution index (Zc)⁶ and the geo-accumulation index (Igeo) were used. Igeo is widely applied to characterize the ecological status of technogenic soils, as coal mining dumps are enriched with metal elements that are released in considerable quantities during natural weathering processes, predominantly in the form of fine particles (Chakraborty et al., 2023). For each element, Igeo was calculated using the following equation (Ghrefat et al., 2011; Martinez and Poletto, 2014):

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n} \right),$$

where C_n is the trace element concentration in the surface soil horizon, B_n is the trace element concentration in the surface horizon of a background soil sample, and 1.5 is a factor introduced to account for natural fluctuations in element concentrations in environments with minimal anthropogenic impact.

Based on Igeo values, seven classes of soil pollution are distinguished: Igeo < 0 – uncontaminated; 0 < Igeo < 1 – slightly to moderately contaminated; 1 < Igeo < 2 – moderately contaminated; 2 < Igeo < 3 – moderately to heavily contaminated; 3 < Igeo < 4 – heavily contaminated; 4 < Igeo < 5 – heavily to extremely contaminated; Igeo > 5 – extremely contaminated.

Statistical analysis was performed using Microsoft Excel LTSC MSO (16.0.14332.20714), Past 4.03, and Statistica 4.03. Soil parameters were compared using the Kruskal–Wallis test. Differences between mean values were considered statistically significant at a confidence level of 95% or higher (p < 0.05). The relationship between enzyme activity and soil properties was examined using regression analysis, also with a 95% confidence level.

Results and discussion

Morphological properties of soils

The profile-genetic classification of soils in technogenic landscapes, developed by researchers from Novosibirsk (Androkhanov, 2005; Kurachev and Androkhanov, 2002), indicates that the soil cover of Kuzbass is primarily represented by four types of embryozems: initial embryozems (Ei), organo-accumulative embryozems (Eo), soddy embryozems (Es), and humus-accumulative embryozems (Eh). The formation of embryozems most commonly occurs under automorphic conditions, owing to the absence of a permanent groundwater table, the high stoniness of the parent materials, and the lack of aquicludes under conditions of strong intra-landscape drainage (Androkhanov et al., 2004).

The substrate of the studied dumps consists of a mixture of overburden and host rocks, including mudstone, siltstone, and sandstone.

Study site no. 1 (N 53.684575° E 86.897874°) is located on a dump where dumping ceased in 2013–2014. The topography of the site is leveled, with depressions and embankments up to 1 m in height. In microdepressions, erosion gullies and evidence of water accumulation are observed. The soil cover is represented by initial embryozems and organo-accumulative embryozems.

Initial embryozem (Fig. 1A), sampled at point T13, occurs in an area surrounded by herbaceous-arboreal vegetation: willows (*Salix* spp.), common aspen (*Populus tremula* L.), box elder (*Acer negundo* L.), and shrubs of sea buckthorn (*Hippophae rhamnoides* L.). The proportion of woody vegetation is approximately 5% of the total projective cover. The herbaceous layer consists of representatives of the Compósitae and Fabaceae families: common dandelion (*Taraxacum officinale* F.H. Wigg.), common mugwort (*Artemisia vulgaris* L.), blue cornflower (*Centaurea cyanus* L.), and red clover (*Trifolium pratense* L.). The profile thickness of the initial embryozem is about 20 cm and can be conditionally divided into two horizons. The surface horizon C₁ (0–7 cm) is heterogeneous dark gray with brown mottles, compacted, structureless, light loamy, with occasional herbaceous roots. It contains inclusions of overburden rock fragments (medium and fine size), with stoniness reaching up to 60%. The boundary is

⁶ SanPiN 1.2.3685-21. Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans.

marked by changes in density and the appearance of coarse rock fragments. Below, to a depth of 20 cm, horizon C₂ is grayish-brown, overcompacted, structureless, light loamy, with occasional herbaceous roots. Inclusions of overburden rock fragments exceed 10 cm in size, and stoniness reaches 80%.

Organo-accumulative embryozem (T14) (Fig. 1B) has developed under herbaceous vegetation consisting of representatives of the Compósitae, Fabaceae, Caryophyllaceae, and Poaceae families: common dandelion (*Taraxacum officinale*), common mugwort (*Artemisia vulgaris*), chickweed (*Stellaria* spp.), red clover (*Trifolium pratense*), alfalfa (*Medicago sativa* L.), rough meadow-grass (*Poa trivialis* L.), smooth brome (*Bromus inermis* Leyss.), quackgrass (*Elytrigia repens* (L.) Desv. ex Nevski), cock's-foot (*Dactylis glomerata* L.), and others. The profile thickness of the organo-accumulative embryozem is about 30 cm and consists of three horizons. On the surface, there is a litter layer (A₀) composed of last year's herbaceous plant residues at weak to moderate stages of decomposition. Beneath the litter lies horizon C₁ (1–6 cm), which is black in color (due to a high content of coal particles), moist, loose, structureless, and light loamy. It is permeated with herbaceous roots and contains inclusions of coal particles. The boundary is slightly wavy, with a transition marked by changes in density and stoniness. Below, to a depth of 25 cm, horizon C₂ is gray, moist, overcompacted, structureless, and light loamy. It contains inclusions of coal particles and coarse rock fragments, occasional herbaceous roots, and stoniness reaches up to 80%.

Study site no. 2 (N 53.662241° E 86.923276°) is located on a 40-year-old, naturally revegetating internal dump with a south-facing slope. The soil cover is represented by two soil types: soddy embryozems and humus-accumulative embryozems. The topography of the site is leveled and gently undulating.

Soddy embryozem (T16) (Fig. 1C) occurs in an area where tree–shrub vegetation is present along the perimeter and sparsely in the center. The tree layer (7% of total vegetation) consists of Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth), and common aspen (*Populus tremula* L.). The shrub layer includes sea buckthorn (*Hippophae rhamnoides* L.) and willows (*Salix* spp.). The herbaceous vegetation (90% projective cover) is represented by a forb–grass mixture: meadow fescue (*Festuca pratensis* Huds.), rough meadow-grass (*Poa trivialis* L.), smooth brome (*Bromus inermis* Leyss.), cock's-foot (*Dactylis glomerata* L.), timothy (*Phleum pratense* L.), common dandelion (*Taraxacum officinale* F.H. Wigg.), meadow vetchling (*Lathyrus pratensis* L.), creeping thistle (*Cirsium arvense* (L.) Scop.), and field sow-thistle (*Sonchus arvensis* L.). The profile thickness of the soddy embryozem is about 30 cm and can be conditionally divided into four horizons. The litter layer (A₀) is dry, light gray, and consists of weakly decomposed herbaceous plant residues from the previous year, along with 2–3-year-old litter at various stages of decomposition. The sod horizon (A_d) (2–5 cm) is dark gray, moist, loose, with a crumb structure, and medium loamy. It is densely permeated with herbaceous roots. The boundary is slightly wavy, with a transition marked by changes in density and the presence of rock fragments. The

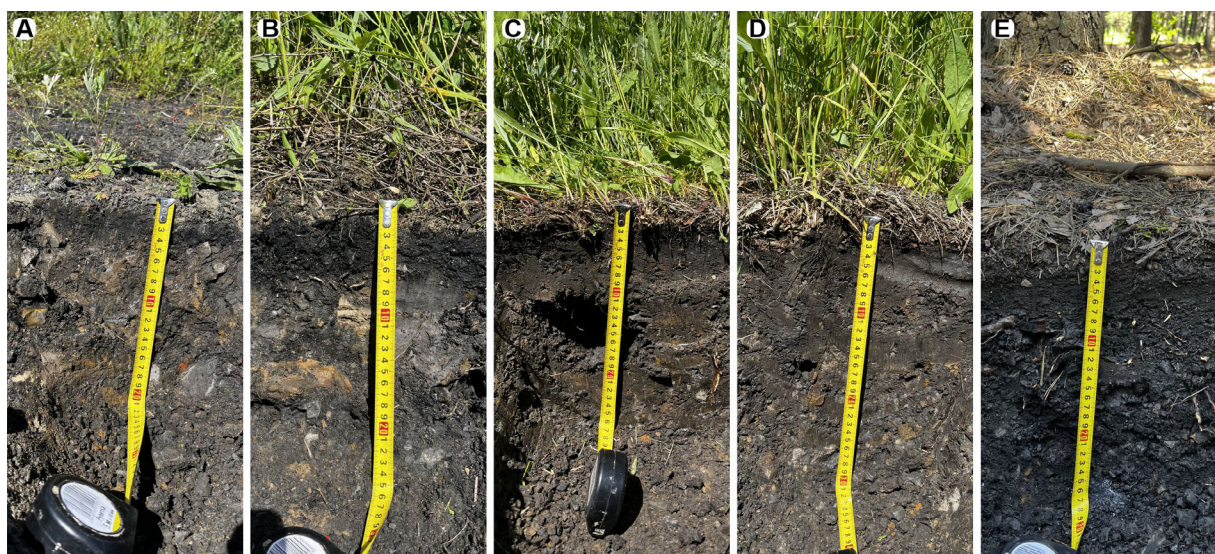


Fig. 1. Profiles of embryozems: **A** – initial embryozem (T13), **B** – organo-accumulative embryozem (T14), **C** – soddy embryozem (T16), **D** – humus-accumulative embryozem (T15), **E** – organo-accumulative embryozem (T17).

transitional horizon AC (5–13 cm) consists of a mixture of overburden and host rocks; it is gray, moist, dense, structureless, and medium loamy. Herbaceous roots are present. The boundary is slightly wavy, with a transition marked by changes in density and the abundance of rock fragments. Rock fragments crumble during excavation; stoniness reaches up to 50%. Below, to a depth of 27 cm, horizon C (13–27 cm) is gray, moist, overcompacted, structureless, and medium loamy, with occasional herbaceous roots. This horizon consists of a mixture of overburden and host rocks; rock fragments crumble during excavation, and stoniness reaches up to 80%.

Humus-accumulative embryozem (T15) (Fig. 1D) occurs in the same area as the soddy embryozem. The profile thickness is about 30 cm and can be conditionally divided into five horizons. The litter layer (A_0) is dry, light gray, and consists of weakly decomposed herbaceous plant residues from the previous year, along with 2–3-year-old litter at moderate to advanced stages of decomposition. The sod horizon (A_0), 5 cm thick, is dark gray, moist, loose, with a crumb–granular structure, and medium loamy. It is densely permeated with herbaceous roots. The boundary is slightly wavy, with a transition marked by a decrease in root abundance. The dark humus horizon A_u (5–7 cm) is dark gray, moist, loose, with a crumb–granular structure, and medium loamy. It is permeated with herbaceous roots and contains occasional rock fragments. The boundary is slightly wavy, with a transition marked by changes in density. The transitional horizon AC (7–17 cm) is dark gray, moist, compacted, with weakly developed crumb structure, and medium loamy. Occasional herbaceous roots are present. Rock fragments at moderate stages of weathering occur as inclusions. Stoniness reaches up to 50%. The transition is marked by changes in density and the abundance of rock fragments. Below, horizon C (17–30 cm) is gray with brown mottles from sandstone, moist, overcompacted, structureless, and medium loamy. Occasional herbaceous roots are present. Stoniness in this layer is approximately 70%.

Study site no. 3 (N 53.394036° E 86.553524°) is located on a dump where forest reclamation was carried out approximately 40 years ago through the planting of pine and sea buckthorn (the latter has now almost completely perished). At present, the site supports a forest with sparse ground vegetation due to the dense pine stands. The topography is leveled, with microdepressions. The soil cover is represented by organo-accumulative embryozems. Organo-accumulative embryozem (T17) (Fig. 1E) occurs under a planting of Scots pine (*Pinus sylvestris* L.). Herbaceous vegetation is nearly absent, with only occasional individuals of wild strawberry (*Fragaria vesca* L.) and greater celandine (*Chelidonium majus* L.). In areas where Scots pine has died out, silver birch (*Betula pendula* Roth), common aspen (*Populus tremula* L.), and rowan (*Sorbus aucuparia* L.) have become established. The profile thickness of the embryozem is about 30 cm and can be conditionally divided into three horizons. The litter layer (A_0) is light gray and consists of pine needle litter at undecayed, partially decomposed, and well-decomposed stages; it is dry in the upper part and moist at the base. Beneath the litter lies horizon C_1 (5–12 cm), which is dark gray, moist, dense, structureless, and light loamy. It contains inclusions of tree roots, rock fragments, and coal particles. Stoniness ranges from 50% to 60%. The boundary is slightly wavy, with a transition marked by the abundance of coarse rock fragments. Below, horizon C_2 (12–27 cm) is dark gray, moist, overcompacted, structureless, and light loamy. It contains inclusions of tree roots and consists of a mixture of overburden and host rocks. Stoniness reaches approximately 90%.

Soil properties

The primary parent material for the development of embryozems is the dump substrate, consisting of coarse fragments of overburden and host rocks. Over time, these fragments undergo weathering, and the soil profile becomes differentiated in the content of coarse and fine fractions (Gossen and Belanov, 2011). At the current stage of pedogenesis, as a result of weathering processes, the fine-earth fraction predominates in the upper layer (0–5 cm) of all embryozem types except for the initial embryozem (Fig. 2). The highest fine-earth content and the lowest bulk density are observed in the surface soil layers, due to enhanced physical and biological weathering driven by climatic conditions and vegetation development. Density increases with depth in embryozems, as does the content of rock fragments of various sizes.

The initial embryozem is slightly alkaline throughout the profile ($pH_{H_2O} = 8.9$), as are the lower layers of the other embryozems (Fig. 3). This is attributed to the alkalinity of the parent materials (Bragina et al., 2014) and the presence of calcium carbonate in the dump rocks (Kolpakova et al., 2024). The actual acidity (pH_{H_2O}) of the upper layers in the other embryozem types is neutral, ranging from 7.0 to 7.2, and remains stable across the sequence from organo-accumulative to soddy to humus-accumulative embryozems (Fig. 3). Exchangeable acidity (pH_{KCl}) decreases with progressive soil development (Fig. 3).

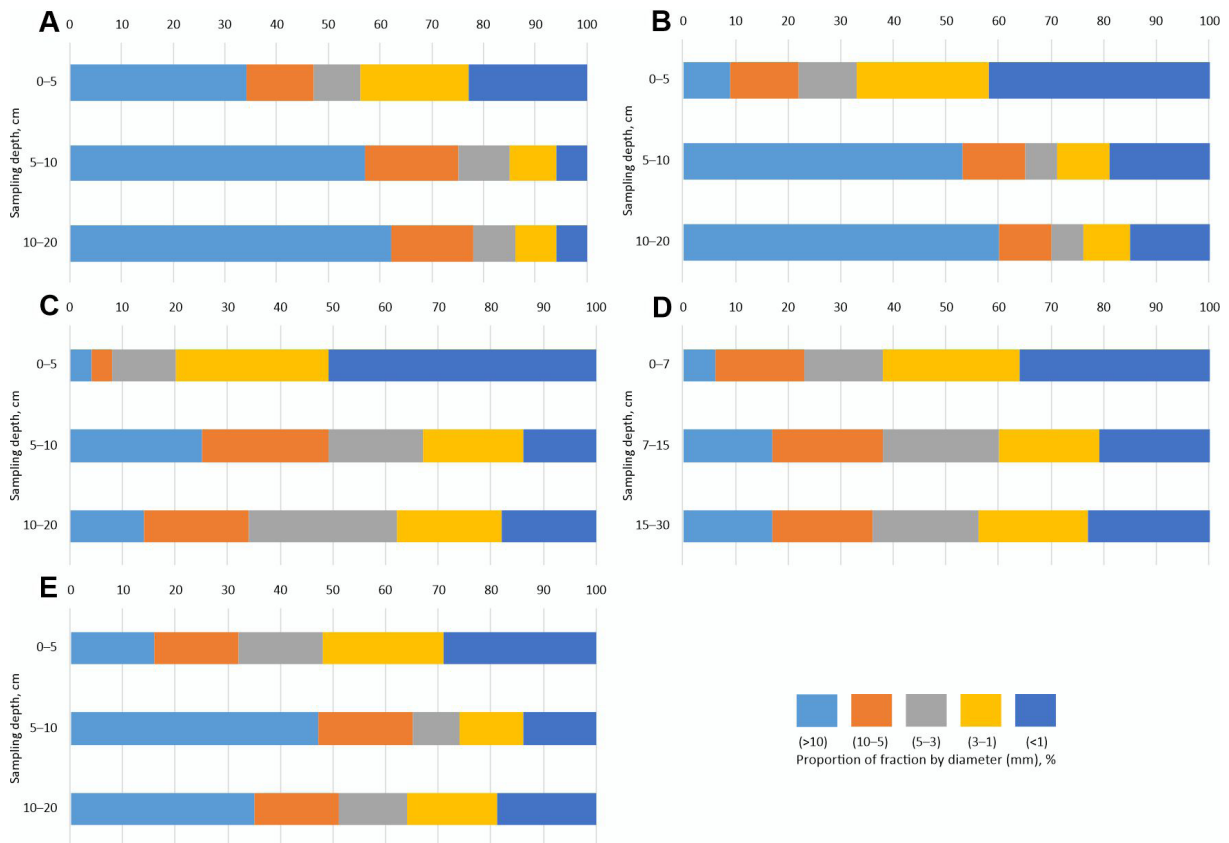


Fig. 2. Particle-size composition of embryozems: **A** – initial embryozem (T13), **B** – organo-accumulative embryozem (T14), **C** – soddy embryozem (T16), **D** – humus-accumulative embryozem (T15), **E** – organo-accumulative embryozem (T17).

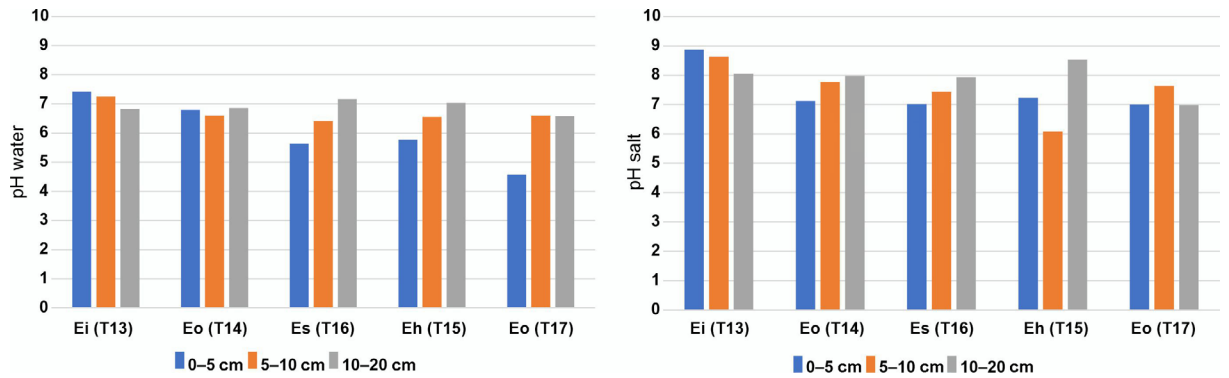


Fig. 3. Acidity of embryozems (for T15, sampling depths: 0–7, 7–15, and 15–30 cm).

The decline in alkalinity may result from plant root exudates, which are typically acidic, as well as from the accumulation of carbon dioxide produced during the mineralization of plant residues. It should be noted that pH_{KCl} responds more rapidly to changes in embryozem acidity during pedogenesis than does $\text{pH}_{\text{H}_2\text{O}}$. A similar trend of decreasing soil pH with development has been observed in soils of varying ages at a reclaimed coal mine in the Raniganj coalfield, India (Kumar et al., 2015), where the decline in pH is explained by the accumulation of organic matter, exchangeable cations, and the fine-earth fraction.

The organic matter (OM) content in the embryozems is very high, reaching up to 28% (Fig. 4), and decreases severalfold with depth. The observed OM content in the embryozems is associated with the presence of coal particles. Mineralogical analysis of soils from coal dumps has revealed high carbon concentrations (Kolpakova et al., 2024). The OM content in the embryozems also exceeds the values typical of background soils (Seredina et al., 2012). The highest OM content is found in the upper layers of the initial embryozem (T13) and the organo-accumulative embryozem (T14) at study site no. 1 (Fig. 4). In the upper part of the profile of the soddy embryozem (T16) and the humus-accumulative embryozem (T15) at study site no. 2, organic matter accumulation horizons (A_0 and A_u) are distinguished (Figs. 1C, D). However, as noted above, such high values (12–14%) indicate substrate heterogeneity and the presence of coal particles within the profiles of the studied soils. The organo-accumulative embryozem at study site no. 3 contains between 9% and 12% organic matter (Fig. 4), with the highest concentration observed in the surface layer.

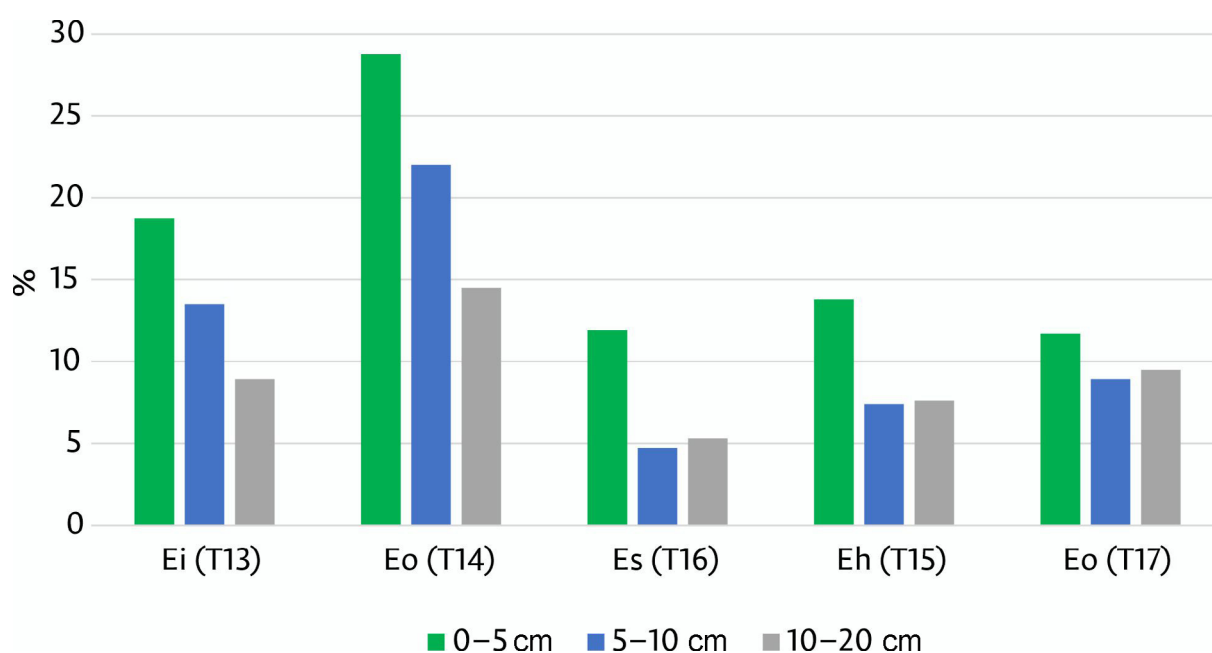


Fig. 4. Organic matter content in the studied soils.

Soil formation proceeds with the participation of enzymes, which accelerate biochemical reactions (Seredina et al., 2012). It is known that during pedogenesis, each soil type develops a specific level and ratio of enzyme activities, which directly influences the intensity and direction of soil biochemical processes (Evdokimova and Kalmykova, 2008; Khaziev, 1982). Soil enzymes are involved in the biogeochemical cycling of carbon, nitrogen, and phosphorus, making them useful as early sensitive indicators of changes in soil (Liu et al., 2021).

Catalase participates in redox processes that underlie the synthesis of humic substances (Zinchenko, 2021) and is also involved in the decomposition of hydrogen peroxide into oxygen and water. Catalase is sensitive to changes in soil conditions, including temperature, acidity, and aeration (Novoselova and Volkova, 2017). Urease facilitates the breakdown of urea into ammonia and carbon dioxide, which do

not entirely volatilize but instead lead primarily to the formation of ammonium bicarbonate (Gizatova and Shipaeva, 2016). The product of urea hydrolysis – ammonia – serves as a direct source of nitrogen nutrition for higher plants (Zinchenko and Zinchenko, 2020).

In the studied soils, higher catalase activity (CA) was observed under well-developed herbaceous communities in areas with soddy and humus-accumulative embryozems (Fig. 5). The increase in catalase activity with the development of an organogenic layer and humus accumulation appears to be related to greater availability of organic matter, a finding supported by studies of technogenic soils in various regions (Evdokimova and Kalmykova, 2008; Li et al., 2015; Pulikova et al., 2024).

Urease activity (UA) is highest in the initial embryozem and lowest in the humus-accumulative embryozem (Fig. 5). In this case, the enzyme activity is most likely determined by the total organic matter content, from both pedogenic and lithogenic sources. According to the scale for assessing soil enzyme enrichment proposed by D.G. Zvyagintsev (Valkov et al., 2004), the initial embryozem (T13), organo-accumulative embryozem (T14), and soddy embryozem (T16) exhibit moderate urease enrichment, whereas the humus-accumulative embryozem (T15) and the organo-accumulative embryozem (T17) are characterized as poor in this enzyme. A correlation was found between organic matter content and urease activity ($R^2 = 0.72$). D.-s. Bai et al. (2022) demonstrated that urease activity is elevated in the rhizosphere zone compared to underlying soil horizons. The increase in urease activity during embryozem development may be associated with increased plant biodiversity and greater projective cover along the sequence from initial to humus-accumulative embryozems, which in turn promotes fine-earth formation and the accumulation of organic matter and nutrients in the soils (Kumar et al., 2015).

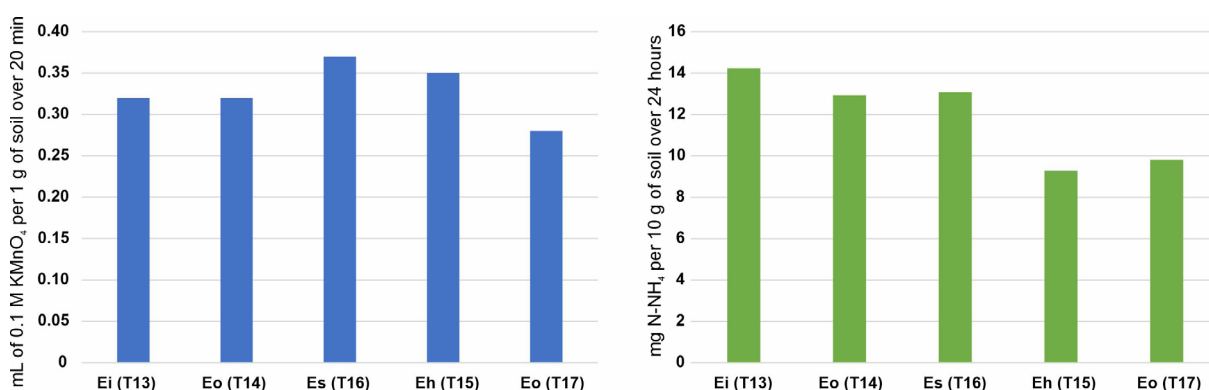


Fig. 5. Mean catalase (A) and urease (B) activity in the upper layers (0–5 cm) of embryozems.

Ecological and geochemical assessment of the studied soils

Chernozem was used as the background for trace element concentrations (Boguslavskiy et al., 2021). Along the sequence of embryozem development, no clear trend in trace element content was observed; however, as alkalinity decreased, the concentrations of Cu, Zn, and Ni increased (Table 1). In the embryozems, elevated levels of Zn, Pb, Cu, Ni, and As were recorded relative to the background. The elevated levels are associated with the presence of these elements in the minerals of overburden rocks (Biswas et al., 2022; Islam et al., 2021). The concentrations of Cd, Pb, Hg, As, and Mo in the studied soils exceed the Vinogradov clarke values (Kasimov and Vlasov, 2015).

Calculation of the total pollution index (Z_c) for the surface layer (0–10 cm) of embryozems in the forest-steppe zone of Kuzbass classified them as soils with a permissible level of pollution ($Z_c < 16$) (Table 1). It should be noted that soils and technogenic substrates of the Taldinsky coal deposit in Kuzbass are also characterized by permissible index values (Ovsyannikova et al., 2020).

Table 1. Total trace element content in technogenic soils of the forest-steppe zone (mg/kg) and heavy metal pollution indices. Zc – total pollution index; * – Zc calculated for the 0–10 cm layer (root zone) relative to background concentrations of chemical elements in chernozems of the forest-steppe zone of Kuzbass (Boguslavskiy et al., 2021); ** – MPC/APC according to SanPIN 1.2.3685-21 (pH KCl >5.5). Italic values indicate exceedance of background levels; grey highlight indicates exceedance of MPC/APC according to SanPIN 1.2.3685-21; bold values indicate exceedance of Vinogradov clarke values. Dashes indicate no data.

Sampling location	Soil (sampling point)	$\frac{\sum_{i=1}^n C_i}{\sum_{i=1}^n C_{i0}}$	pH _{KCl}	Element												
				Zn	Cd	Pb	Hg	Cu	Co	Ni	As	Mo	Ba	Be	Li	Zc
Coal mining dumps of the forest-steppe zone of Kuzbass	Initial embryozem (T13)		7.4	95.40	2.00	15.38	0.11	25.77	14.54	34.06	62.35	1.31	494.63	2.84	47.47	7.11
	Organo-accumulative embryozem (T14)		6.7	57.18	1.43	10.73	0.16	22.72	9.81	22.86	52.70	0.92	318.37	1.95	43.49	5.79
	Soddy embryozem (T16)	0–10	6.2	22.76	2.52	22.56	0.17	20.81	14.33	35.91	2.45	1.19	329.5	2.56	45.52	1.74
	Humus-accumulative embryozem (T15)		6.0	23.31	2.48	23.69	0.30	33.24	13.83	36.92	2.52	1.15	377.59	2.64	48.67	1.83
	Organo-accumulative embryozem (T17)		5.6	142.17	1.89	18.69	0.12	60.75	26.81	73.28	71.61	1.96	464.38	2.88	48.4	10.98
Background – chernozem*		–	95	–	13	–	33	–	37	9	1.55	–	–	–	–	
MPC/APC** according to SanPIN 1.2.3685-21 ⁷		–	/220.0	/2.0	/130.0	2.1/	/132.0	–	/80.0	/10.0	–	–	–	–	–	
Clarke values after A.P. Vinogradov (Kasimov and Vlasov, 2015)		–	83	0.13	16.00	0.0043	47.00	18.00	58.00	1.70	1.1	650	3.8	–	–	

⁷ SanPIN 1.2.3685-21. Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans.

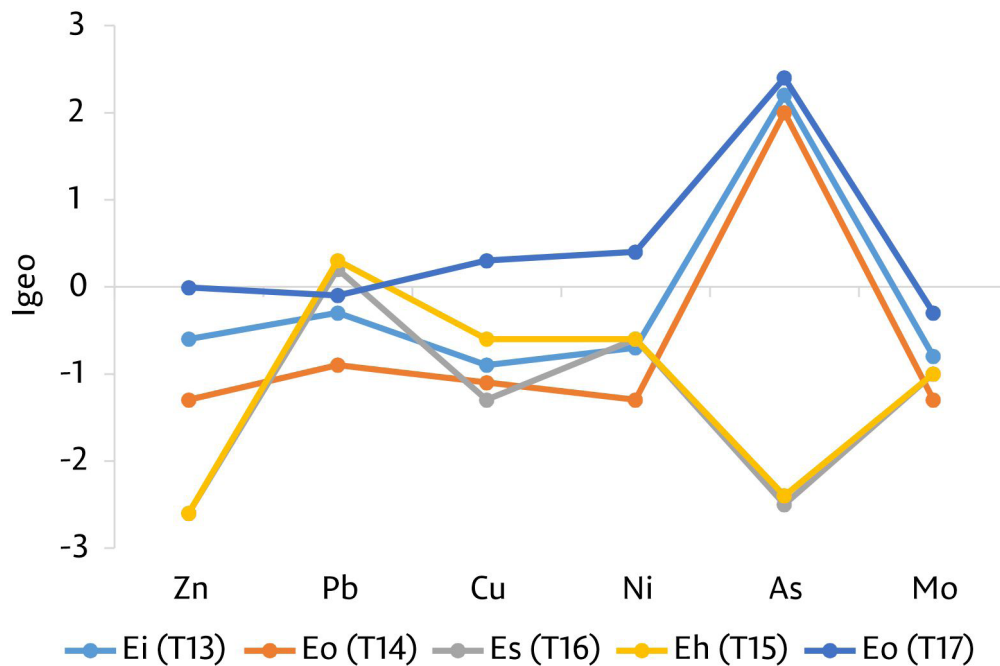


Fig. 6. Geo-accumulation index (I_{geo}) for trace elements.

The I_{geo} index indicated arsenic contamination in the initial embryozem (T13) and the organo-accumulative embryozem (T14) (Fig. 6). In the study by Siddique et al. (2020), I_{geo} values pointed to significant accumulation of As and Zn in soils near the Barapukuria coal mine in Bangladesh. For the soddy embryozem (T16) and the humus-accumulative embryozem (T15), slight to moderate lead contamination was recorded. Arsenic contamination, along with such chalcophile elements as lead and cadmium, is characteristic of coal-mining landscapes (Abliz et al., 2018). The organo-accumulative embryozem (T17) exhibited contamination with Cu, Ni, and As. The I_{geo} index is widely used for soil assessment, including in coal mining areas. For instance, soils of the open-cast mine in the eastern Raniganj coalfield, India, show slight contamination with Co, Cu, Ni, Cd, and Cr, which is likely associated with coal-mining activity (Chakraborty et al., 2023; Dutta et al., 2025).

Conclusion

Initial, organo-accumulative, soddy, and humus-accumulative embryozems were identified on the studied coal dumps in the forest-steppe zone of Kuzbass. In the embryozems, the fine-earth fraction increases during pedogenesis. Due to the increase in the proportion of fine-earth material and the development of plant communities, the bulk density of the technogenic soils decreases.

The reaction of the aqueous extract in the embryozems ranges from strongly alkaline to neutral along the sequence from initial to organo-accumulative to soddy to humus-accumulative embryozems. Organic matter content in the studied soils is heterogeneous due to the inclusion of coal particles and varying degrees of soil development, including vegetation. The highest organic matter content was found in the organo-accumulative embryozem. The initial embryozem exhibited moderate urease activity, while the remaining soils showed low urease activity. Catalase activity in the technogenic soils increases with the development of the organogenic layer and the accumulation of humus.

Ecological and geochemical assessment of the surface layer (0–10 cm) of the embryozems based on the total pollution index classified them as soils with a permissible level of pollution. Analysis of the I_{geo} index showed that Pb, Cu, and Ni concentrations correspond to slight to moderate contamination, while the soils are moderately to heavily contaminated with As, and no contamination with Zn or Mo was detected.

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