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

Rationale for the application parameters of unmodified iron-magnesium production waste as a nature-like ameliorant for cadmium immobilization

Natalya Yu. Antoninova✉, Artem V. Sobenin, Albert I. Usmanov, Yaroslava A. Kuznetsova

Institute of Mining of the UB RAS, Ekaterinburg, Russia

***How to cite this article*:** Antoninova N.Yu., Sobenin A.V., Usmanov A.I., Kuznetsova Ya.A. Rationale for the application parameters of unmodified iron-magnesium production waste as a nature-like ameliorant for cadmium immobilization. Journal of Mining Institute. 2026. Vol. 281. Iss. 2, p. 22-34.

Abstract

An assessment is presented regarding the use of iron-magnesium production waste for the remediation of cadmium-contaminated soils. The waste contains, mg/kg: Mg 175,000, Fe 52,000, K 30,000, and traces of Cu, Zn, and Co, with no detectable Cd. Garden cress (*Lepidium sativum* L.) was grown for seven days on a substrate containing 10 mg/l Cd and treated with three doses of an iron-magnesium composite (IMC): 10, 60, and 120 g/m^2. $FeSO_4$, $MgSO_4$, and a combination thereof were used for comparison. Parameters evaluated included germination rate, root length, pH, redox potential, mineralization, moisture content, and metal concentrations in soil and plants (via atomic absorption spectrophotometry); root barrier coefficients (RBC) and translocation factor (TF) were calculated. The high IMC dose (T4, 120 g/m^2) maximized Cd immobilization (reducing the mobile fraction by 38 % to 9.6 mg/kg), eliminated Mg deficiency, and stimulated root growth by 30.6 %, but caused soil salinization (TDS up to 740 mg/l) and the accumulation of Ni (up to 39.8 mg/kg) and Co (up to 5.2 mg/kg) in the soil. The low dose (T6, 10 g/m^2) reduced Cd availability to 11 mg/kg and increased root growth by 10.4 % without significant salinization (TDS 270 mg/l). Ni and Co were effectively retained by the roots (RBC 1.96 for Ni, >3.0 for Co), and their transport to the shoots was minimal (TF 1.26 for Ni, 0.60 for Co). For short-term application, a dosage of 120 g/m^2 is justified, provided salinity is monitored. The optimal long-term solution is a dosage of 10 g/m^2.

Keywords

soil remediation; cadmium; iron-magnesium waste; industrial waste; ameliorants; biotesting; nature-like materials; root barrier coefficient; translocation factor; secondary contamination

Funding

This article was prepared within the framework of State assignment 075-00408-26-00 N 125070908250-1, topic 2 “Geoinformation support for the systemic assessment of nature-conservation strategies during subsurface resource development” (FUWE-2025-0002).

Received: 09.04.2026 ***Accepted: 25.06.2026*** ***Online: 30.10.2026*** ***Published: 30.10.2026***

Introduction

Soil contamination with heavy metals, particularly cadmium (Cd), is a critical issue in the development of environmental protection measures [1, 2]. Cadmium is characterized by high mobility in natural environments [3, 4], toxicity [5], and the potential for bioaccumulation and entry into food chains [6], posing serious risks to human health and ecosystem stability [7]. The primary sources of cadmium entering the environment are mining and metallurgical facilities [8, 9], and agricultural activities, including the use of phosphate fertilizers [10, 11].

The most common measure for reducing the bioavailability of heavy metals is the application of chemical ameliorants such as limestone (lime) flour and phosphorites capable of immobilizing toxic elements [11]. However, the effectiveness of these methods is inconsistent and depends heavily on

This is an open access article under the CC BY 4.0 license

specific soil conditions. Studies show that in soils systematically fertilized with liquid manure, liming while raising the pH simultaneously increases cadmium mobility. This effect is attributed to the formation of stable, mobile Cd-fulvate complexes during the alkalization of an organically contaminated medium [11]. An alternative amendment, glauconite-bearing phosphorite flour, demonstrates a more stable (albeit weaker) immobilizing effect; however, its sorption capacity drops sharply regarding organo-mineral forms of the metal [11]. The inconsistent performance of traditional approaches to these challenges is confirmed by other studies [12]. In peat soils, the use of slaked lime especially combined with mineral fertilizers (NPK) led to the highest levels of cadmium accumulation in plants, whereas the application of natural zeolite resulted in reduced bioavailability to plants [12]. These findings indicate that the effectiveness of traditional ameliorants depends heavily on specific soil conditions and does not always guarantee the desired outcome. Consequently, there is a pressing need to identify new, more versatile, and environmentally safe materials for cadmium immobilization that can ensure a stable effect without requiring complex optimization of specific environmental parameters. The use of industrial waste specifically from iron-magnesium production appears to be a promising avenue, as these materials can serve as nature-like ameliorants.

Current research into the remediation of contaminated land is shifting toward the development of highly effective composite and modified materials. Natural and modified sorbents represent promising avenues of study. Composite materials based on natural minerals (such as attapulgite) and waste products (oyster shells) demonstrate a synergistic effect by combining high adsorption capacity (up to 197 mg/g for Cd) with the ability to regulate soil acidity, thereby further reducing metal mobility [13]. Another area of focus involves functionalized biochars. Chemical modification of biochar for instance, with potassium permanganate significantly enhances its potential as an immobilizing soil amendment. Such materials can reduce Cd bioavailability in soil by 43 % and its accumulation in crops by 66 % [14]. Innovative solutions, such as biochar-based hydrogels enriched with phosphate-solubilizing bacteria, combine up to 98 % cadmium adsorption with the delivery of essential phosphorus to plants, thereby boosting soil fertility [15].

The general trend involves the development of “nature-like” technologies that facilitate comprehensive environmental remediation through the synergy of multiple mechanisms such as sorption, precipitation, and pH modification while simultaneously addressing the utilization of secondary raw materials. Mining industry waste specifically from iron-magnesium production [16, 17], appears particularly promising in this regard, as it contains compounds capable of sorbing heavy metals and altering soil acid-base and redox properties. This approach enables the use of waste materials to reduce the mobility and bioavailability of cadmium in contaminated soils, aligning with the principles of waste recycling and resource conservation.

Thus, the aim of this study is to substantiate the parameters (optimal dosages and application conditions) for using unmodified waste from iron-magnesium production as a highly targeted, nature-like soil amendment for cadmium immobilization in contaminated soils. To achieve this aim, the following objectives have been set:

- evaluate the dose-dependent effect of iron-magnesium waste on the physicochemical parameters of soils (pH, redox potential, total mineralization, moisture content);
- investigate the effect of the ameliorant on the bioavailability of cadmium for the test crop by assessing its accumulation in roots and shoots;
- conduct a comprehensive assessment of the ameliorant’s concurrent impact on the migration of other chemical elements (Ni, Co, Cu, Zn, Fe, Mn, Mg, K) to rule out the risk of secondary contamination;
- determine, based on the analysis, safe and effective application rate ranges for the waste regarding cadmium immobilization.

This is an open access article under the CC BY 4.0 license

Materials and methods

Objects of study. *Substrate*. The soil used in this study was collected from the experimental research site of the Institute of Mining of the UB RAS (Fomino village, Sysertsky District, Sverdlovsk Region). The site is subject to anthropogenic impact due to past agricultural cultivation and construction activities, as well as its proximity (approximately 15 m) to a roadway. The soil is classified as a grey forest soil with a heavy texture and a granular-nutty structure; its reaction is near-neutral. To simulate substrates typical of intensive vegetable farming, the soil was mixed with peat-based growing medium in a 7:3 ratio. Intensive vegetable production frequently employs multi-component substrates containing peat, which are often contaminated with cadmium due to the use of mineral fertilizers. Substrates of similar composition were previously tested in our experiments aimed at identifying ameliorants capable of immobilizing cadmium [18].

Test culture. Garden cress (*Lepidium sativum* L.) was used as the test organism. This crop was selected due to its short growing season and sensitivity to heavy metal contamination.

Ameliorants. The starting material consists of chrysotile-asbestos beneficiation tailings, which are classified as serpentinites. Magnesium compounds are extracted from these wastes, a process that also generates secondary paste-like waste classified as hazard class 3 [15, 16]. The MPC/APC values (maximum permissible concentrations and approximate permissible concentrations) listed in Table 1 are based on SanPiN 1.2.3685-21 “Hygienic standards and requirements for ensuring the safety and/or harmlessness of environmental factors for humans”. In CIS countries, the total volume of accumulated serpentinite waste exceeds 500 million tonnes [19]. Its elemental composition is characterized by high levels of magnesium (175,000 mg/kg), iron (52,000 mg/kg), and potassium (30,000 mg/kg), as well as the presence of trace amounts of copper, zinc, and cobalt, which require monitoring. The cadmium content in the waste is below the detection limit, thereby minimizing the risk of direct contamination.

Table 1

Elemental composition of materials (total content), mg/kg

Cu	Mg	Fe	Zn	Cd	Co	Ni	Mn	K
Unmodified iron-magnesium production waste								
41.3±1.1	175,000 ± 3500	52,000±2000	77.7±1.8	< 0.037	119.8±1.4	3083±48	1010±35	30,140±787
Substrate								
7.10±0.87	1610±40	10,600±250	42.3±1.8	0.68±0.20	4.20±0.65	22.30±1.1	190.50±3.5	4370±90
MPC/APC								
–/132	–	–	–/220	–/2	–	–/80	1500/–	–

Prior to use, the iron-magnesium composite (IMC) was dried at 105°C and sieved through a 1 mm mesh. For comparative analysis, iron sulfate $FeSO_4$ (T3), magnesium sulfate $MgSO_4$ (T2), and a combination thereof (T1) were used as conventional materials widely employed in agriculture. The sulfate dosage of ~14 g/m^2 corresponds to the average agronomic application rate for most crops.

Modeling of cadmium contamination. Soil contamination with cadmium was simulated by applying a solution prepared from a certified reference material (State CRM 7874-2000). A solution with a Cd concentration of 10 mg/l was applied at a rate of 10 ml per 60 g of air-dried soil. Following application, the soil was left for two weeks to reach sorption equilibrium. The concentration of mobile cadmium forms in the soil after treatment was 15.4±3.9 mg/kg.

This is an open access article under the CC BY 4.0 license

Experimental procedure. The experiment was conducted in Petri dishes with a diameter of 100 mm (surface area 0.00785 m^2). Amendment dosages were calculated based on the dish area: 10 g/m^2 of IMC corresponded to 0.08 g per dish (T6); 60 g/m^2 to 0.5 g (T5); 120 g/m^2 to 0.9 g (T4); and for sulfates (T1-T3), 14 g/m^2 corresponded to 0.1 g per dish. The weighed amendment was thoroughly mixed with 60 g of contaminated soil until a homogeneous mixture was obtained. The resulting substrate was placed in Petri dishes, moistened with distilled water, and left for two days to stabilize. Garden cress (*Lepidium sativum* L.) seeds were sown on the surface (without burial), in accordance with the cultivation practices for this crop. The experiment was performed in triplicate. The growing period lasted seven days, following the seed manufacturer's recommendations (the maturation period for garden cress is 8±2 days). By this time, a fully developed plant had formed, suitable for assessing metal accumulation and redistribution within the system root – shoot. Upon completion, relative seed germination (RGP) and relative root length (RRG) indices were calculated and subsequently evaluated [12, 13].

Sample preparation. Plant samples were ashed in accordance with GOST 26929-94 using the TEMOS-EXPRESS sample preparation system (ITM LLC, Russia), with a stepwise temperature increase from 250 to 450 °C. The resulting ash was treated with nitric acid, evaporated, and calcined at 300 °C; this cycle was repeated until the ashing process was complete. In the final stage, the ash was moistened with nitric acid, and the solution was quantitatively transferred to a test tube.

Determination of total metal forms in soil. Sample preparation was performed using a MARS 5 microwave system (CEM Corporation, USA) in accordance with EPA Method 3052. To a 0.5 g sample, 9 ml of HNO_3 and 3 ml of HF were added; the mixture was allowed to stand for 15 min, then heated to 180 °C over 6 min and held at that temperature for 10 min at a power of 1800 W in sealed EasyPrep vessels. After cooling, the volume was adjusted to 50 ml, yielding a clear solution.

Determination of mobile metal forms in soil. Mobile acid-soluble forms of metals were determined by extracting soil samples with one-dimensional solution of nitric acid at a mass-to-volume ratio of 1:10. To do this, 5 g of soil was placed in 50 ml of one-dimensional solution of nitric acid and agitated on a rotator.

Analytical methods. Metal concentrations (Cu, Zn, Cd, Co, Mg, Fe, Ni, K) in plants and soil were determined using flame atomic absorption spectrometry in an air-acetylene flame (Varian AA 240 fs, Varian Australia Pty Ltd.) [12, 13, 17]. Key physicochemical parameters pH, redox potential (ORP), total dissolved solids (TDS), and moisture content were measured in the soil substrates.

Assessment of metal translocation. To analyze the redistribution of elements within the soil-root-shoot system, two main coefficients were calculated [12, 13]:

- root barrier coefficient (RBC), indicating the ability of roots to retain the element (RBC > 1);
- translocation factor (TF), reflecting the degree of element accumulation in the above-ground part of the plant from the soil (TF > 1).

Statistical significance of differences between experimental treatments was assessed using analysis of variance and Tukey's test at $p < 0.05$.

The permissible application rate of IMC was calculated using the method of S.E.Vitkovskaya:

$$PAR = (0.8\ MPC_p - C_b)\ M_p / (C - C_b)\ T,$$

where MPC_p is the standard value from SanPiN 1.2.3685-21; C_b is the element content in the soil prior to application; M_p is the mass of the arable layer, M_p = 3000 t/ha; C is the element content in the ameliorant; and T is the application period, T = 1. The lowest calculated dose was considered the limiting factor.

Results discussion

An analysis of modern methods for remediating cadmium-contaminated soils has revealed that, while most existing approaches successfully immobilize the metal, they often fail to comprehensively account for environmental factors, potentially leading to secondary contamination. Furthermore, many effective ameliorants are either costly or require complex modification. Consequently, there is a pressing

This is an open access article under the CC BY 4.0 license

need to identify accessible, nature-like materials capable of immobilizing cadmium even those with inherent limitations (such as the introduction of associated elements) provided that the associated risks are managed. The use of iron-magnesium production waste as a nature-like soil amendment warrants further investigation, accompanied by a mandatory assessment of potential side effects.

Iron and magnesium compounds are natural key components of soil minerals [20-22]. Iron hydroxides and oxides contained in such wastes, due to their developed specific surface area, are one of the most effective natural sorbents of heavy metals [23, 24]. However, to eliminate the risk of secondary contamination, a comprehensive assessment of the impact of the sorbent is necessary. It is important to analyze both the biological response of the ecosystem and changes in the soil environment. Indicators of growth and development of garden cress (*Lepidium sativum* L.) and physicochemical properties of the soil when adding various materials are presented in Table 2. A comprehensive analysis of all indicators makes it possible to compare in detail the influence of various ameliorants on the plant-soil system under conditions of cadmium stress [25, 26]. In terms of the key parameter of initial development – RGP – all treatment options demonstrated 100 % efficiency. The subsequent development of sprouts, assessed by the RRG parameter, revealed significant differences. Maximum stimulation of root formation, exceeding the level of pure control by 30.6 %, was achieved when adding a dose of 120 g/m^2 (T4) of iron-magnesium waste. The combined application of iron and magnesium sulfates (T1) also showed a significant positive result, increasing root length by 14.7 %, while their separate application (T2, T3) and a waste dose of 10 g/m^2 (T6) provided a moderate but stable increase. The unexpectedly low efficacy of the 60 g/m^2 waste dose (T5), comparable only to the suppressed cadmium control, indicates the presence of a narrow dosage range where negative factors, likely related to osmotic stress, outweigh the protective effect.

Table 2

Development of garden cress (*Lepidium sativum* L.) and physicochemical properties of the soil

Parameter	RGP, %	RRG, %	pH	ORP, mV	TDS, mg/l	*W*, %
K	100.0±0.0*a*	100.0±0.0*d*	5.90±0.10*bc*	191±3*b*	279±5*a*	7.98±0.14*a*
KCd	83.3±1.4*b*	91.7±1.6*a*	5.86±0.10*bc*	213±4*a*	283±5*a*	7.92±0.14*a*
T1	100.0±0.0*a*	114.7±1.12*b*	5.48±0.09*a*	187±3*b*	302±5*a*	7.96±0.14*a*
T2	100.0±0.0*a*	109.2±0.2*c*	5.58±0.09*ac*	169±3*c*	302±5*a*	7.99±0.14*a*
T3	100.0±0.0*a*	109.6±0.8*c*	5.84±0.10*bc*	205±3*d*	326±6*b*	7.89±0.14*a*
T4	100.0±0.0*a*	130.6±0.5*e*	6.80±0.12*e*	128±2*f*	740±13*e*	9.05±0.16*b*
T5	100.0±0.0*a*	108.9±3.2*c*	6.29±0.11*d*	187±3*b*	550±10*d*	8.98±0.16*b*
T6	100.0±0.0*a*	110.4±0.7*c*	5.97±0.22*c*	204±4*d*	270±5*a*	8.28±0.15*a*

Note. Different latin letters indicate statistically significant differences between groups ($p < 0.05$); identical letters indicate the absence of statistically significant differences; K – clean peat substrate; KCd – cadmium-contaminated peat.

The impact on the physicochemical properties of the soil varied depending on the nature of the amendment. Sulfates (T1-T3) caused slight acidification of the soil solution, with pH values shifting from 5.48 to 5.84. In contrast, the industrial waste IMC acted as an active alkaline agent, with an effect that was strictly dose-dependent ranging from a minor shift at the low dose (T6, pH 5.97) to distinct alkalization (T4, pH 6.80). Such a change in pH is, in itself, a powerful factor in the immobilization of cadmium ions. The effect on redox conditions was equally pronounced. While cadmium contamination itself raised the ORP (Cd control 213 mV), the various ameliorants modulated this parameter in different directions – magnesium sulfate (T2, 169 mV) significantly lowered it, whereas iron sulfate (T3, 205 mV) and the low dose of waste (T6, 204 mV) raised it. The greatest reduction in ORP indicating the creation of a reducing environment was observed with the application of the high dose of waste (T4, 128 mV).

Sulfates and the low waste dosage did not result in statistically significant soil salinization, keeping levels comparable to the control variants (270-302 mg/l). Applications of the technogenic waste at rates of 60 g/m^2 (T5) and 120 g/m^2 (T4) caused a dose-dependent increase in mineralization 2-fold

This is an open access article under the CC BY 4.0 license

and 2.7-fold, respectively, relative to the control samples thereby creating a direct risk of osmotic stress for more sensitive plant crops. A significant increase in soil moisture *W* was observed only with the application of medium (T5, 8.98 %) and high (T4, 9.05 %) waste dosages, a phenomenon likely attributable to the material's hygroscopic properties.

Thus, the comparison reveals two alternative approaches. The first, involving a combination of sulfates (T1), ensures effective plant protection and root system stimulation without inducing adverse changes in the soil complex. The second, based on the use of an industrial waste product, demonstrates high efficacy in mitigating cadmium stress and stimulating growth. However, this efficacy is achieved through a transformation of the soil environment, involving alkalinization, salinization, and alterations to the redox status.

Based on the data from the correlation matrix presented in Fig.1, the following conclusions can be drawn regarding the interrelationships between the parameters under study. The most significant correlation is observed between indicators characterizing the physicochemical properties of the soil. The Pearson correlation coefficient *r* between total mineralization and soil moisture is 0.91, indicating a nearly functional direct relationship. Equally strong direct correlations were recorded between soil acidity and mineralization ($r = 0.89$), as well as between acidity and moisture ($r = 0.88$). The increase in total mineralization is driven by the input of soluble waste components and sulfates; these simultaneously increase osmotic pressure and promote moisture retention in the soil solution [27], thereby resulting in a direct correlation between TDS and *W*. The relationship between pH and TDS arises because the alkaline components of the solid municipal waste fraction increase the pH upon dissolution [28]. Consequently, an increase in pH is accompanied by a rise in mineralization, a trend reflected by the correlation coefficient of $r = 0.89$.

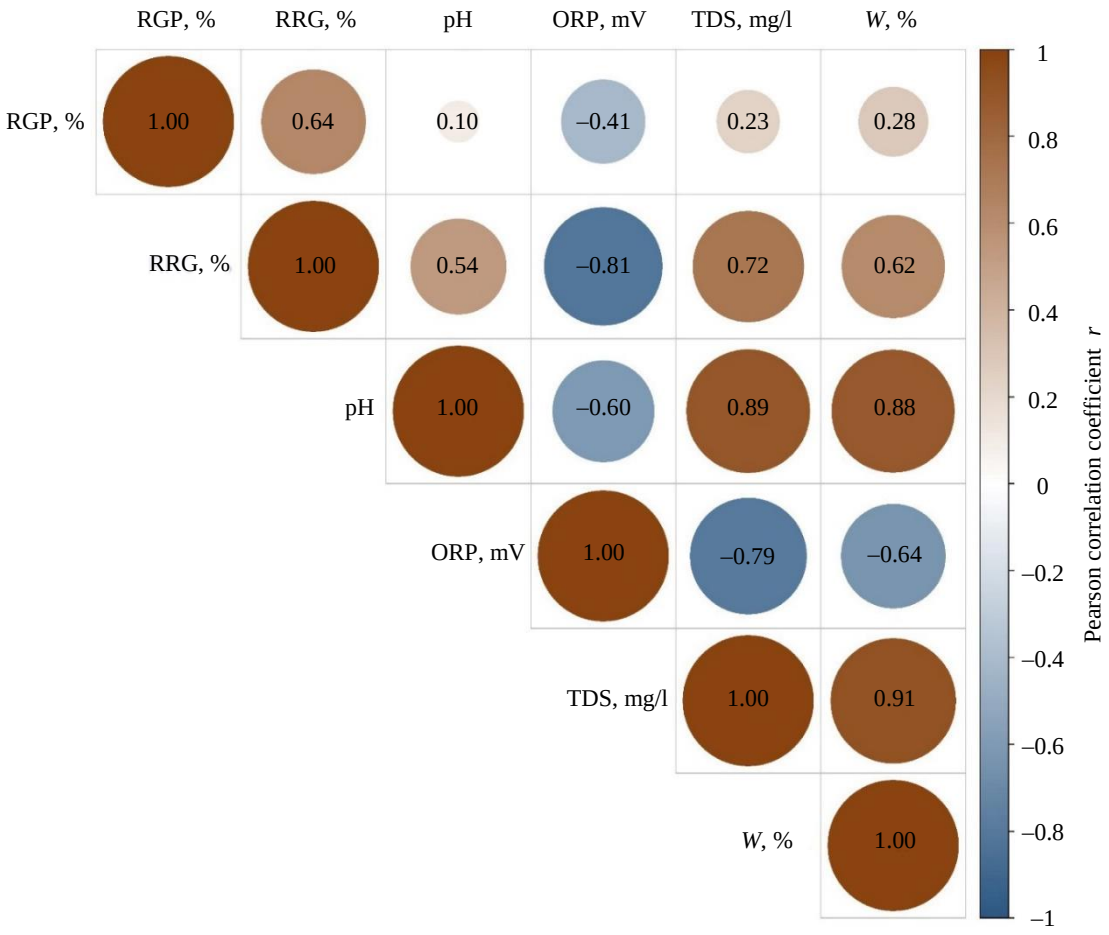


Fig.1. Correlation matrix of growth and development parameters of garden cress (*Lepidium sativum* L.) with soil parameters upon the application of various materials

This is an open access article under the CC BY 4.0 license

A key indicator of plant development – relative root length – shows a strong positive correlation with soil salinity (r = 0.72) and moisture content (r = 0.62), as well as a moderate association with soil acidity (r = 0.54). However, the most pronounced relationship is the strong negative correlation between root length and ORP, with a coefficient of –0.81. This indicates that improved root system growth is statistically linked to a shift in redox conditions toward a more reducing state. Redox potential, in turn, is inversely related to TDS (r = –0.79) and pH (r = –0.60); specifically, soil alkalization and salinization induced by the soil amendment contribute to a decrease in ORP, a process that correlates with root development under stress conditions.

Thus, correlation analysis statistically confirms that the effect of treatments particularly with the technogenic waste (T4-T6) – on garden cress characteristics does not occur in isolation but rather within the context of transformations in the soil environment. These transformations are manifested as an increase in pH, total salt content, and moisture level, alongside a decrease in ORP.

The primary factor determining the effectiveness of ameliorants is the behavior of cadmium within the system soil – root – shoot [29, 30]. The elemental composition of the soil and garden cress (*Lepidium sativum* L.) plants following the application of various materials (T1-T6) is presented in Table 3. Maximum permissible concentration values are based on the Customs Union Technical Regulation TR CU 021/2011 “On food safety” (as amended on April 22, 2024). While the total cadmium content in the soil remained high across all treated variants (14.2-15.4 mg/kg in the Cd control and variants T1-T3), the application of iron-magnesium production waste (IMC) statistically significantly reduced the soil concentration to 9.6, 11.2, and 11 mg/kg for variants T4-T6, respectively (Fig.2). In contrast, the application of iron and magnesium sulfates (T1-T3) did not result in a statistically significant reduction of cadmium content in the soil, indicating a different mechanism of protective action [30]. In the variants treated with magnesium and iron sulfates (T1-T3), garden cress roots accumulated the highest amounts of cadmium – 19.8, 21.8, and 22.1 mg/kg, respectively which is substantially higher than the 0.97 mg/kg observed in the Cd control. Cadmium translocation to the shoots under these treatments was significantly lower – 17.8, 11.4, and 22.7 mg/kg for variants T1-T3, respectively, compared to 38.8 mg/kg (KCd). A different pattern was observed in the variant with the high dose of IMC (T4): the cadmium content in the roots was 11.9 mg/kg – 1.6-1.9 times lower than with sulfate treatments while the content in the shoots was only 9.2 mg/kg. This supports the strategy wherein cadmium immobilization in the soil limits its uptake by the plant as a whole [31-33].

Alongside the dynamics of cadmium, the materials influenced the plants supply of other elements (Table 3). Cadmium stress in the KCd control treatment caused magnesium and iron deficiencies in the roots – Mg content dropped from 5,333 to 1,069 mg/kg, and Fe content from 7,145 to 2,158 mg/kg. Magnesium deficiency was most effectively alleviated in the T4 variant, where root Mg content rose to 10,263 mg/kg 9.6 times higher than the level in the KCd control and soil Mg content reached 4,801 mg/kg (6.5 times higher than the KCd control). Sulfates also increased magnesium and iron levels in the roots compared to the KCd control, though their effect was less pronounced.

However, the application of the technogenic waste IMC, particularly at high doses, resulted in soil contamination with associated toxic elements. For instance, the nickel content in the soil of treatment T4 was 39.8 mg/kg – 3.9 times higher than the 10.3 mg/kg found in the control while the cobalt content was 5.22 mg/kg, compared to 1.22 mg/kg in the untreated control. These elements were also actively taken up by the root system; nickel concentrations in the roots reached 97.9 mg/kg, and cobalt concentrations reached 9.60 mg/kg. However, their translocation to the shoots was significantly lower – 49.9 mg/kg for nickel and 3.15 mg/kg for cobalt.

Manganese concentration in the roots dropped sharply from 382.6 mg/kg in the unpolluted control to 62.4 mg/kg under contamination conditions. All ameliorants restored manganese levels to varying degrees, reaching, for example, 281.0 mg/kg with the application of a high dose of IMC (T4). Ferrous sulfate (T3) also promoted significant accumulation of copper (22.5 mg/kg in roots) and zinc (45.3 mg/kg in roots and 85.2 mg/kg in shoots) within plant tissues. Potassium content in the shoots increased by 45 % (from 110,614 to 160,605 mg/kg) due to cadmium exposure, whereas in the roots, it decreased by half (from 48,257 to 23,436 mg/kg). All treatments studied with the exception of ferrous sulfate (T3, 234,369 mg/kg in shoots) normalized the elevated potassium levels in the shoots, reducing them to values in the range of approximately 100,000-130,000 mg/kg.

This is an open access article under the CC BY 4.0 license

Elemental composition of substrates and garden cress plants (*Lepidium sativum* L.), mg/kg

Parameter	Cu	Zn	Cd	Co	Mg	Mn	K	Ni	Fe
					Substrate				
K	3.08±0.57*a*	11.3±1.6*ab*	0.37±0.15*b*	1.22±0.25*bc*	748±83*a*	111.6±15.2*a*	1975±153*ab*	10.3±1.8*a*	4664±536*a*
KCd	2.87±0.51*a*	10.8±1.3*a*	15.4±3.9*a*	1.48±0.58*abc*	738±177*a*	105.8±25.3*a*	1945±180*ab*	11.5±3.5*a*	4907±1215*a*
T1	6.31±0.40*b*	11.2±1.3*ab*	14.5±1.2*a*	1.56±0.19*abc*	930±355*ab*	108.2±26.1*a*	1669±163*cd*	19.5±5.0*b*	4915±1354*a*
T2	4.48±1.12*c*	11.1±1.4*ab*	14.9±1.9*a*	1.08±0.14*b*	1174±366*b*	108.9±25.1*a*	1797±150*ac*	11.1±3.2*a*	5015±1834*a*
T3	2.72±0.80*a*	11.4±1.2*ab*	14.2±1.2*a*	2.06±0.40*a*	756±245*a*	107.9±33.0*a*	2146±225*b*	28.0±7.5*c*	4895±1536*a*
T4	4.97±1.41*c*	13.5±1.8*b*	9.6±1.2*c*	5.22±2.10*d*	4801±1120*c*	179.2±45.1*b*	1563±163*d*	39.8±10.7*d*	7291±2634*b*
T5	3.77±0.66*ac*	11.9±1.8*ab*	11.2±1.4*c*	3.34±1.02*e*	2387±650*d*	150.7±25.4*c*	2085±190*b*	33.2±9.7*e*	5857±2105*c*
T6	2.59±0.41*a*	10.8±1.2*a*	11.0±1.7*c*	1.81±0.44*ac*	1764±435*e*	114.0±20.2*a*	1735±150*cd*	25.2±12.0*f*	4558±1865*a*
MPC/APC	3/–	23/–	–	5/–	–	500/–	–	4/–	–
					Roots				
K	13.5±1.0*bc*	32.3±2.0*a*	0.81±0.05*a*	2.96±0.21*bc*	5333±484*d*	382.6±37.6*e*	48257±4457*b*	183.9±15.1*f*	7145±795*d*
KCd	16.3±1.0*a*	32.5±1.8*a*	0.97±0.07*a*	< 0.41	1069±87*a*	62.4±5.7*a*	23436±2336*a*	9.33±0.78*a*	2158±178*a*
T1	15.9±0.8*ab*	32.7±2.0*a*	19.8±1.4*b*	2.22±0.18*b*	2981±251*bc*	275.2±25.2*bc*	21927±1927*a*	52.3±4.2*b*	4462±362*b*
T2	12.2±0.7*c*	37.9±2.1*ab*	21.8±1.5*b*	0.85±0.07*a*	4016±402*bcd*	213.9±16.1*b*	47256±3744*b*	20.8±2.1*a*	2562±255*ac*
T3	22.5±1.1*d*	45.3±2.7*c*	22.1±1.6*b*	4.05±0.32*c*	2706±236*b*	220.9±19.1*bc*	40677±3823*bc*	75.3±6.7*c*	3565±354*bc*
T4	15.9±0.9*ab*	24.0±1.4*d*	11.9±0.8*c*	9.60±0.77*d*	10263±843*e*	281.0±29.0*c*	20451±2049*a*	97.9±8.8*d*	3725±374*b*
T5	19.3±1.0*e*	37.2±2.2*ab*	15.8±1.0*d*	9.19±0.69*d*	8270±830*f*	262.5±22.5*bc*	33356±2556*c*	127.2±10.2*e*	3625±365*bc*
T6	19.3±1.0*e*	40.9±2.0*bc*	14.7±1.1*cd*	< 0.41	4306±430*cd*	132.4±10.6*d*	17700±1770*a*	28.4±2.3*a*	2417±197*a*
					Shoots				
K	8.78±0.45*df*	62.2±3.7*a*	0.73±0.04*g*	< 0.41	4647±372*abd*	112.4±9.0*abc*	110614±8849*bc*	5.78±0.46*b*	935±75*c*
KCd	7.57±0.45*ab*	69.9±3.5*a*	38.8±1.9*a*	< 0.41	4551±364*ab*	123.1±9.8*ab*	160605±12848*a*	150.7±12.1*a*	600±48*a*
T1	6.67±0.34*ac*	85.2±4.3*b*	17.8±0.9*b*	< 0.41	5946±476*acd*	136.0±10.9*a*	130510±10441*ab*	6.64±0.53*b*	389±31*b*
T2	6.38±0.32*c*	68.3±3.4*a*	11.4±0.6*cd*	< 0.41	4009±401*b*	91.0±9.1*c*	98542±9854*bc*	6.45±0.52*b*	331±33*b*
T3	9.34±0.47*de*	85.2±4.3*b*	22.7±1.1*e*	< 0.41	9593±768*e*	165.2±13.2*d*	234369±18749*d*	9.19±0.74*b*	1111±89*c*
T4	8.26±0.41*bdf*	70.1±3.5*a*	9.2±0.5*c*	3.15±0.19*b*	6367±509*c*	124.2±9.9*ab*	101813±8145*bc*	49.9±4.0*c*	1419±114*d*
T5	7.78±0.39*abf*	72.3±3.6*a*	12.3±0.6*d*	2.05±0.12*c*	6031±603*cd*	106.7±10.7*bc*	117395±11739*bc*	31.6±2.5*d*	968±97*c*
T6	10.0±0.5*e*	69.9±3.5*a*	15.1±0.8*f*	< 0.41	6786±543*c*	107.6±8.6*abc*	95812±7665*c*	9.30±0.74*b*	624±50*a*
MPC	–	–	0.03	–	–	–	–	–	–
					Maximum permissible application rate				
IMC, t/ha	8640	11330	–	70.3	–	3695	–	40.9	–

This is an open access article under the CC BY 4.0 license

Journal of Mining Institute. 2026. *Vol. 281. Iss. 2. P. 22-34*

© Natalya Yu. Antoninova, Artem V. Sobenin, Albert I. Usmanov, Yaroslava A. Kuznetsova, 2026

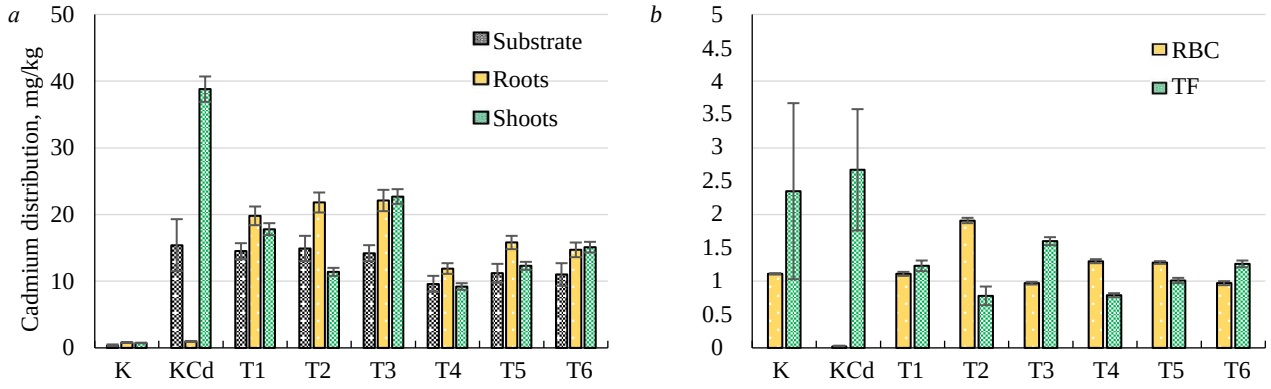


Fig.2. Cadmium distribution in the substrate – root – shoot system of garden cress (*Lepidium sativum* L.) at different amendment dosages: *a* – in the substrate, roots, and shoots; *b* – root barrier (RBC) and translocation (TF) coefficients

Iron deficiency was observed in the roots, where the iron content decreased 3.3-fold (from 7,145 to 2,158 mg/kg). This deficiency was effectively corrected by both sulfate treatments (e.g., to 4,462 mg/kg in the T1 variant) and IMC waste (to 3,725 mg/kg in the T4 variant). A distinctive effect of the high IMC dose (T4) was the suppression of zinc accumulation in the roots to a minimum level of 24.0 mg/kg. Thus, the ameliorants do not merely immobilize cadmium but also actively restructure the plant's overall elemental status, correcting specific imbalances caused by the toxicant [34, 35].

Elemental analysis confirms that the observed improvement in growth parameters particularly in treatment T4 results from a complex redistribution of elements. A high dose of IMC implements a cadmium-exclusion strategy by immobilizing the metal in the soil and simultaneously alleviating magnesium deficiency, though it also stimulates the accumulation of other metals (Ni, Co) within the system. Cadmium levels in cress shoots exceeded the MPC (Table 3) is an expected outcome, given that the soil had been artificially contaminated with high doses to clearly demonstrate the redistribution process. Sulfates, meanwhile, allow cadmium uptake by the roots but block its translocation, thereby mitigating nutrient imbalance without causing secondary soil contamination [30, 31].

The calculation of the PAR for the IMC, performed using the standards set forth in SanPiN 1.2.3685-21 (total forms for Cd, Cu, Zn, Ni, and Mn, and the mobile form for Co, see Table 1), demonstrated that nickel is the limiting element (MPC 40.9 t/ha). The experimental application rates (10-120 g/m^2, corresponding to 0.01-0.12 t/ha) are two to three orders of magnitude lower than the calculated PAR for nickel, confirming the safety of using the soil ameliorant within the studied dosage range.

Calculating the RBC and TF for garden cress (*Lepidium sativum* L.) specimens grown on Cd-contaminated substrates with the application of various cadmium-immobilizing materials (Table 4), allows for an objective assessment of the root system's efficiency in performing its barrier function: retaining the toxic element and preventing its transfer to the above-ground biomass [36, 37]. A decrease in RBC values resulting from the use of a soil amendment would directly indicate a compromise of this barrier and increased translocation, signaling a potential environmental risk.

Calculating the TF made it possible to assess the plant's ability to accumulate the element from the soil [38]. The accumulation factor can serve as a key indicator for evaluating a crop's phytoremediation potential (if TF > 1) or, conversely, for determining the safety of the harvested produce (if the TF tends toward a minimum).

In the control (KCd), the RBC was low – 0.023, indicating a complete failure of the barrier function and massive metal translocation to the shoots, where the TF reached 2.67. All applied ameliorants fundamentally altered this situation, vastly increasing the efficiency of cadmium retention in the roots. Magnesium sulfate (T2) exhibited the highest RBC value for Cd – 1.91, while the lowest total uptake (TF = 0.78) was observed in this same treatment and in the high-dose IMC (T4) (TF = 0.79). Notably, the barrier function regarding cadmium remained high in treatments T4 and T5 (RBC = 1.30 and 1.28, respectively). These findings support strategies involving either active cadmium retention in the roots (T2) or the restriction of uptake through soil immobilization (T4) [31-33].

This is an open access article under the CC BY 4.0 license

Root and shoot biomass values for garden cress (*Lepidium sativum* L.) specimens, g/m^2

Parameter	Cu	Zn	Cd	Co	Mg	Mn	K	Ni	Fe
				RBC					
K	1.53±0.03*e*	0.52±0.00*bd*	1.11±0.01*b*	–	1.15±0.02*h*	3.40±0.06*d*	0.43±0.01*b*	31.80±0.1*f*	7.63±0.24*d*
KCd	2.16±0.01*a*	0.46±0.01*ab*	0.023±0.01*a*	–	0.23±0.01*a*	0.50±0.01*a*	0.14±0.01*a*	0.06±0.01*a*	3.59±0.01*ab*
T1	2.38±0.01*b*	0.38±0.01*ac*	1.11±0.03*b*	–	0.50±0.00*b*	2.02±0.03*b*	0.17±0.00*a*	7.88±0.00*b*	11.5±0.02*c*
T2	1.92±0.02*c*	0.56±0.06*d*	1.91±0.04*c*	–	1.00±0.00*c*	2.35±0.06*b*	0.48±0.01*b*	3.23±0.06*c*	7.74±0.01*d*
T3	2.40±0.01*b*	0.53±0.01*bd*	0.97±0.02*d*	–	0.28±0.00*d*	1.35±0.23*c*	0.17±0.03*a*	8.19±0.07*b*	3.24±0.57*ab*
T4	1.93±0.01*c*	0.34±0.04*c*	1.30±0.03*e*	3.06±0.43*a*	1.61±0.00*e*	2.28±0.42*b*	0.20±0.04*a*	1.96±0.02*d*	2.65±0.47*a*
T5	2.47±0.00*d*	0.51±0.01*bd*	1.28±0.02*e*	4.48±0.08*b*	1.37±0.00*f*	2.46±0.04*b*	0.28±0.05*c*	4.06±0.7*e*	3.80±0.76*b*
T6	1.93±0.00*c*	0.59±0.06*d*	0.97±0.03*d*	–	0.63±0.02*g*	1.23±0.00*c*	0.18±0.01*a*	3.05±0.00*c*	3.87±0.01*b*
				TF					
K	2.93±0.66*abe*	5.57±0.53*b*	2.35±1.32*ab*	–	6.23±0.20*c*	1.00±0.03*ab*	56.0±1.1*b*	0.57±0.11*a*	0.20±0.00*e*
KCd	2.67±0.31*ab*	6.58±1.13*ab*	2.67±0.91*a*	–	6.32±1.03*c*	1.16±0.04*b*	82.5±3.5*c*	13.14±0.48*b*	0.12±0.02*d*
T1	1.06±0.12*c*	7.60±0.18*a*	1.23±0.08*ab*	–	6.39±0.48*c*	1.26±0.11*b*	78.2±6.5*c*	0.34±0.03*a*	0.08±0.01*c*
T2	1.42±0.04*cd*	6.18±0.51*ab*	0.78±0.14*b*	–	3.42±0.33*a*	0.83±0.05*a*	54.8±5.2*b*	0.58±0.09*a*	0.06±0.01*b*
T3	3.43±0.07*ae*	7.47±0.24*a*	1.60±0.06*ab*	–	12.69±0.92*d*	1.53±0.06*b*	109.2±9.2*d*	0.33±0.03*a*	0.23±0.02*f*
T4	1.68±0.22*cd*	5.22±0.56*b*	0.79±0.03*b*	0.60±0.03*a*	1.33±0.11*a*	0.69±0.06*a*	65.1±5.5*b*	1.26±0.11*a*	0.19±0.02*e*
T5	2.10±0.31*bd*	6.12±0.70*ab*	1.01±0.04*b*	0.61±0.03*a*	2.54±0.36*ab*	0.72±0.13*a*	56.3±5.5*b*	0.95±0.08*a*	0.17±0.02*e*
T6	3.88±0.51*e*	6.47±0.45*ab*	1.26±0.05*ab*	–	3.85±0.18*ab*	0.94±0.08*ab*	55.2±2.3*b*	0.37±0.03*a*	0.14±0.02*d*

© Natalya Yu. Antoninova, Artem V. Sobenin, Albert I. Usmanov, Yaroslava A. Kuznetsova, 2026

This is an open access article under the CC BY 4.0 license

Furthermore, cadmium stress sharply reduced the RBC for magnesium from 1.15 to 0.23 and for manganese from 3.40 to 0.507. The application of ameliorants made it possible not only to restore but, in some cases, even to strengthen this barrier. The result for magnesium in treatment T4 (RBC = 1.61) is particularly notable. Under Cd exposure, a high level of potassium accumulation in the shoots was observed (TF = 82.5, compared to 56.0 in the untreated control). Most ameliorants, particularly T2 (TF = 54.8) and T4 (TF = 65.1), effectively normalized this parameter.

The application of IMC resulted in the appearance of new elements in the system, primarily cobalt and nickel. For cobalt, RBC of 3.06 and 4.48 were recorded in variants T4 and T5, respectively, alongside a relatively low TF of 0.6. This indicates that cobalt introduced via the waste is actively taken up by the roots, but its translocation to the shoots is restricted by the system itself. Nickel, which exhibited a high TF in the cadmium control (TF = 13.14), showed significantly lower accumulation values in the IMC variants (T4, T5; TF = 1.26 and 0.95); this suggests that the forms of nickel introduced with the waste possess lower mobility and bioavailability compared to cadmium.

Thus, the analysis of coefficients confirms that the positive effect of soil ameliorants lies not in completely blocking uptake, but in restructuring the internal distribution of elements – specifically, by creating an effective root barrier against the toxicant while facilitating the transport of essential nutrients and, in the case of IMC, incorporating new trace elements into this redistribution cycle and subsequently retaining them primarily within the below-ground biomass.

Conclusion

The study conducted made it possible to achieve the stated goal and address all the formulated objectives – namely, to substantiate the use of unmodified waste from iron-magnesium production (IMC) as a soil amendment for cadmium immobilization.

It has been established that the application of IMC exerts a dose-dependent effect on the physicochemical properties of the soil. A high dose (120 g/m^2, T4) causes alkalinization (pH rising to 6.8), an increase in total dissolved solids (TDS up to 740 mg/l), a decrease in redox potential to 128 mV, and an increase in moisture content; this creates a reducing, alkaline environment that promotes cadmium immobilization. A low dose (10 g/m^2, T6) does not result in significant salinization or changes in pH.

The iron-magnesium composite acts as an effective immobilizer of cadmium. Application of a high dose resulted in a reduction of mobile Cd forms in the soil to 9.6 mg/kg (compared to 15.4 mg/kg in the Cd control); total accumulation in shoots decreased (TF = 0.79), while the root barrier increased (RBC= 1.30). Furthermore, the cadmium-induced magnesium deficiency was eliminated, stimulating root growth (a 30.6 % increase in length).

The primary environmental risk associated with the application of IMC is secondary soil contamination with nickel and cobalt. In the T4 treatment (120 g/m^2), their soil concentrations increased 3.9- and 4.3-fold, respectively, reaching 39.8 mg/kg for Ni and 5.2 mg/kg for Co. However, the calculated translocation coefficients indicated that while these elements are actively taken up by the roots (high RBC of 3.06 for Co), they are virtually not translocated to the shoots (low TF of 0.60 for Co and 1.26 for Ni). The risk of Ni and Co entering the food chain directly via watercress is minimal; however, their long-term accumulation in the soil warrants further study.

Based on a comprehensive analysis, two potential dose ranges with different efficacy-safety balances have been identified:

- 120 g/m^2 (T4) – ensures maximum Cd immobilization and root growth stimulation, but causes soil salinization and the accumulation of Ni and Co in the soil. It may be used for short-term remediation, provided that subsequent monitoring is carried out;
- 10 g/m^2 (T6) – ensures significant Cd immobilization, stimulates root growth and root barrier formation, without causing statistically significant salinization or pH changes. The uptake of associated toxic elements (Ni, Co) is minimal.

This is an open access article under the CC BY 4.0 license

The presented findings and recommendations serve as a guide for further research and do not constitute a regulation ready for implementation. Future research will involve assessing the dynamics of chemical element accumulation in soil and plants when cultivating various crops on different types of substrates, as well as conducting field trials under open-field conditions.

REFERENCES

1. 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

2. Ankush, Ritambhara, Lamba S. et al. Cadmium in Environment – An Overview. Cadmium Toxicity in Water. Springer, 2024, p. 3-20. DOI: 10.1007/978-3-031-54005-9_1

3. Vasilyeva T.N., Galaktionova L.V. Assessment of the state of urban soils based on the content of pollutants. *Agrarian Bulletin of the Urals.* 2023. Vol. 23. N 12, p. 2-11 (in Russian). DOI: 10.32417/1997-4868-2023-23-12-2-11

4. Shabanov M.V., Marichev M.S., Burachevskaya M.V. et al. Cadmium and lead in the Soimonov valley soil, Karabash: Mobility, bioavailability and ecological risks. *Mining Informational and Analytical Bulletin.* 2025. N 4, p. 104-120 (in Russian). DOI: 10.25018/0236_1493_2025_4_0_104

5. Genchi G., Sinicropi M.S., Lauria G. et al. The Effects of Cadmium Toxicity. *International Journal of Environmental Research and Public Health*. 2020. Vol. 17. Iss. 11. N 3782. DOI: 10.3390/ijerph17113782

6. Zulfiqar U., Ayub A., Hussain S. et al. Cadmium Toxicity in Plants: Recent Progress on Morpho-physiological Effects and Remediation Strategies. *Journal of Soil Science and Plant Nutrition.* 2022. Vol. 22. Iss. 1, p. 212-269. DOI: 10.1007/s42729-021-00645-3

7. Yonggang Ma, Qunchao Su, Chengguang Yue et al. The Effect of Oxidative Stress-Induced Autophagy by Cadmium Exposure in Kidney, Liver, and Bone Damage, and Neurotoxicity. *International Journal of Molecular Sciences*. 2022. Vol. 23. Iss. 21. N 13491. DOI: 10.3390/ijms232113491

8. Myagkaya I.N., Saryg-ool B.Yu., Kirichenko I.S. et al. Ecogeochemical characteristics of the Yarly-Amry and the Chibitka Rivers, located in the dispersion train of Aktash mercury deposit and its wastes (Gorny Altai). *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering.* 2022. Vol. 333. N 4, p. 7-26. DOI: 10.18799/24131830/2022/4/3273

9. Yakovlev E., Druzhinina A., Druzhinin S. et al. Assessment of physical and chemical properties, health risk of trace metals and quality indices of surface waters of the rivers and lakes of the Kola Peninsula (Murmansk Region, North-West Russia). *Environmental Geochemistry and Health*. 2022. Vol. 44. Iss. 8, p. 2465-2494. DOI: 10.1007/s10653-021-01027-5

10. Elsukova E.Yu., Nedbaev I.S., Kuzmina D.S. Monitoring of soil pollution in the area affected by the production of phosphorus fertilizers. *Vestnik of Saint-Petersburg University. Earth Sciences.* 2022. Vol. 67. N 4, p. 652-674 (in Russian). DOI: 10.21638/spbu07.2022.406

11. Pilip L.V., Syrchina N.V. Effect of meliorants on cadmium mobility in soils. *Russian Journal of Applied Ecology.* 2023. N 4, p. 60-66 (in Russian). DOI: 10.24852/2411-7374.2023.4.60.66

12. Utkin A.A., Akanova N.I. The effect of fertilizers and meliorants on the height and bio-mass of mustard, the accumulation of cadmium by plants and the capacity-sorption properties of peat lowland soil. *Plodorodie.* 2024. N 1 (136), p. 75-78 (in Russian). DOI: 10.25680/S19948603.2024.136.19

13. Hongyan Zhu, Yangping Wen, Qingyin Shang et al. Attapulgite/oyster shell composite reduces cadmium and lead bioavailability in acidic agricultural soils through synergistic adsorption and pH regulation. *Scientific Reports*. 2025. Vol. 15. N 15609. DOI: 10.1038/s41598-025-00302-0

14. Liyuan Mu, Hongyin Zhou, Zhengli Lu et al. Passivation effect of modified biochar on cadmium in mining contaminated soil. *Scientific Reports*. 2025. Vol. 15. N 30402. DOI: 10.1038/s41598-025-15860-6

15. Borgohain A., Baruah M., Gogoi R. et al. Integrating cadmium removal and phosphate supplementation by fortified biochar hydrogel for agricultural soil: a novel composite material. *Discover Agriculture*. 2025. Vol. 3. N 273. DOI: 10.1007/s44279-025-00459-2

16. Antoninova N.Yu., Sobenin A.V., Usmanov A.I., Shepel K.V. Assessment of the possibility of using iron-magnesium production waste for wastewater treatment from heavy metals (Cd^{2+}, Zn^{2+}, Co^{2+}, Cu^{2+}). *Journal of Mining Institute.* 2023. Vol. 260, p. 257-265. DOI: 10.31897/PMI.2023.34

17. Antoninova N.Yu., Sobenin A.V., Usmanov A.I., Gorbunov A.A. Substantiation of parameters for the use of nature-like materials based on mining waste as ameliorants. *News of the Ural State Mining University.* 2025. Iss. 3 (79), p. 99-108. DOI: 10.21440/2307-2091-2025-3-99-108

18. Sumiao Sun, Xiaojun Wang, Xuejia Gu et al. Effects of Amendments on Cadmium Adsorption Capacity of Soil and Growth of *Brassica rapa* L. *Heilongjiang Agricultural Sciences*. 2024. Vol. 9, p. 25-34 (in Chinese). DOI: 10.11942/j.issn1002-2767.2024.09.0025

19. Auyeshov A.P., Arynov K.T., Yeskibayeva Ch.Z. Resource and economic efficiency of serpentinite waste utilization for the production of inorganic magnesium compounds. *Academic Scientific Journal of Chemistry.* 2025. Vol. 3. N 464, p. 29-40. DOI: 10.32014/2025.2518-1491.298

20. Belanov I.P., Shipilova A.M., Mezentseva O.P. Mineralogical and granulometric composition of soils formed on the surface of iron ore tailings dumps. *Izvestiya. Ferrous Metallurgy.* 2024. Vol. 67. N 5, p. 542-548. DOI: 10.17073/0368-0797-2024-5-542-548

21. Alekseev A.O., Malyshev V.V., Alekseeva T.V. Mineralogy and Geochemistry of Granulometric Fractions As a Tool for Studying Transformations of Solid Phase of Soils. *Moscow University Soil Science Bulletin.* 2025. Vol. 80. N 1, p. 50-58. DOI: 10.3103/S0147687424700789

This is an open access article under the CC BY 4.0 license

22. Chernousenko G.I., Khitrov N.B., Pankova E.I. Magnesium in Saline Gypsum-Bearing Soils of Russia. *Eurasian Soil Science*. 2023. Vol. 56. N 7, p. 854-867. DOI: 10.1134/S1064229323600537

23. Linnikov O.D., Rodina I.V. Sorption Properties of Freshly Precipitated Iron(III) Hydroxide toward Nickel Ions. Part 1. Mechanism and Efficiency of the Sorption Process. *Protection of Metals and Physical Chemistry of Surfaces*. 2022. Vol. 58. N 6, p. 1116-1124. DOI: 10.1134/S2070205122060107

24. Xin Nie, Erping Bi. Modeling of Cd(II) adsorption on iron (hydr)oxide-organic composites: deviations from additive adsorption in composite sorption systems. *Environmental Earth Sciences*. 2024. Vol. 83. Iss. 8. N 225. DOI: 10.1007/s12665-024-11561-x

25. Qian-hui Zhang, Yi-qi Chen, Zhen-bang Li et al. Defense guard: strategies of plants in the fight against Cadmium stress. *Advanced Biotechnology*. 2024. Vol. 2. Iss. 4. N 44. DOI: 10.1007/s44307-024-00052-6

26. Elatafi E., Elhendawy B., Iqbal S. et al. Physicochemical, Metabolite, Osmolyte Synthesis, and Enzymatic Alterations of Grapevine Rootstocks in Response to Cadmium Stress. *Journal of Soil Science and Plant Nutrition*. 2025. Vol. 25. Iss. 4, p. 9902-9920. DOI: 10.1007/s42729-025-02765-6

27. Rasiah V., Florentine S.K. Characterizing selected soil attributes of different land-use management to assess reforestation benefits of deforested riparian buffers. *Ecological Processes*. 2018. Vol. 7. N 39. DOI: 10.1186/s13717-018-0151-7

28. Savich V.I., Belopukhov S.L., Podvolotskaya G.B. et al. Regarding the problem of interrelation of soils and surface water as landscape components. *Prirodoobustroistvo*. 2018. N 1, p. 76-83 (in Russian). DOI: 10.26897/1997-6011/2018-1-76-83

29. Tianbao Ren, Huilin Feng, Wan Mahari W.A. et al. Biochar and microbial synergy: enhancing tobacco plant resistance and soil remediation under cadmium stress. *Biochar*. 2025. Vol. 7. N 119. DOI: 10.1007/s42773-025-00535-2

30. Qin Yao, Yueying Yang, Jia Chen et al. Soil application of $FeCl_3$ and $Fe_2(SO_4)_3$ reduced grain cadmium concentration in Polish wheat (*Triticum polonicum* L.). *BMC Plant Biology*. 2024. Vol. 24. N 930. DOI: 10.1186/s12870-024-05652-x

31. Wenchao Deng, Guanghui Wang, Bing Wang, Nansheng Deng. Sulfur Modified Biochar Supported Ferrous Sulfide Composite for the Immobilization of Cadmium in Contaminated Soil. *Water, Air, & Soil Pollution*. 2024. Vol. 235. Iss. 8. N 495. DOI: 10.1007/s11270-024-07317-9

32. Jing Ren, Zixuan Zhao, Amjad Ali et al. Characterization of phosphorus engineered biochar and its impact on immobilization of Cd and Pb from smelting contaminated soils. *Journal of Soils and Sediments*. 2020. Vol. 20. Iss. 8, p. 3041-3052. DOI: 10.1007/s11368-019-02403-6

33. Korkmaz H.E., Akgün M., Kocaman A., Korkmaz K. Mitigating cadmium and salinity stress in lettuce through biochar application: impacts on growth and nutrient dynamics. *BMC Plant Biology*. 2026. Vol. 26. N 339. DOI: 10.1186/s12870-025-08051-y

34. Chaw Su Lwin, Young-Nam Kim, Mina Lee et al. In Situ Immobilization of Potentially Toxic Elements in Arable Soil by Adding Soil Amendments and the Best Ways to Maximize Their Use Efficiency. *Journal of Soil Science and Plant Nutrition*. 2024. Vol. 24. Iss. 1, p. 115-134. DOI: 10.1007/s42729-024-01630-2

35. Subašić M., Karalija E., Selović A. Evaluating the impact of intercropping *Silene sendtneri*, a Cd hyperaccumulating plant, on mineral and growth dynamics in *Zea mays* under Cd stress. *Plant and Soil*. 2025. Vol. 517. Iss. 1, p. 699-716. DOI: 10.1007/s11104-025-07889-3

36. Leskova O.A., Bondarevich E.A., Kotsyurzhinskaya N.N. Accumulation and distribution of chemical elements in plants of *Taraxacum officinale* Wigg. (Transbaikal Territory). *Problems of Botany of South Siberia and Mongolia*. 2021. Vol. 20. N 1, p. 265-268 (in Russian). DOI: 10.14258/pbssm.2021051

37. Zorikova O.G., Manyakhin A.Yu. Microelement composition of *Patrinia scabiosifolia* and *Patrinia rupestris*. *Khimiya rastitelnogo syrya*. 2023. N 4, p. 277-287 (in Russian). DOI: 10.14258/jcprm.20230411994

38. Denisova S.G., Reut A.A. Calculation of the arsenic, lead and cadmium accumulation coefficients by aboveground and underground paeonia organs. *Bulletin of KSAU*. 2025. N 4 (193), p. 51-57 (in Russian). DOI: 10.36718/1819-4036-2023-4-51-57

Authors: **Natalya Yu. Antoninova,** *Candidate of Engineering Sciences, Head of Laboratory* (*Institute of Mining of the UB RAS, Ekaterinburg, Russia*), *natal78@list.ru, https://orcid.org/0000-0002-8503-639X*, **Artem V. Sobenin,** *Candidate of Engineering Sciences, Researcher* (*Institute of Mining of the UB RAS, Ekaterinburg, Russia*), *http://orcid.org/0000-0001-5513-5680*, **Albert I. Usmanov,** *Candidate of Engineering Sciences, Researcher* (*Institute of Mining of the UB RAS, Ekaterinburg, Russia*), *http://orcid.org/0000-0002-3650-0467*, **Yaroslava A. Kuznetsova,** *Junior Researcher* (*Institute of Mining of the UB RAS, Ekaterinburg, Russia*), *http://orcid.org/0000-0002-7808-8474*.

The authors declare no conflict of interests.

This is an open access article under the CC BY 4.0 license