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Phytoaccumulation of Heavy Metals in South Kazakhstan Soils (Almaty and Turkestan Regions): An Evaluation of Plant-Based Remediation Potential

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ABSTRACT

Significant environmental concerns are raised by heavy metal pollution in soils, particularly in areas like South Kazakhstan where hazardous materials have accumulated as a result of human activities including mining, industry, and agriculture. This paper presents theoretical and experimental findings regarding the phytoremediation potential of sowing peas (*Pisum sativum*) in the grey soils of South Kazakhstan. Special attention is paid to the determination of gross concentrations of various forms of copper, nickel, and cobalt in the initial and remediated soils. The methodology basis for the study were chemical phase analysis, atomic absorption spectrometry, and X-ray electron microscopy to assess heavy metal levels in soils and plant samples. It was established that in the arid climate of Southern Kazakhstan, the upper layers of the soil up to 40 cm contain the highest concentration of heavy metal ions. The findings of the study will allow predicting the effectiveness of phytoremediation measures. The study suggests that sowing peas have potential for phytoremediation due to their ability to accumulate heavy metals in their root systems and biomass. It highlights the potential of phytoextraction techniques, which involve growing metal-accumulating plants in polluted soils and processing the harvested biomass to recover absorbed metals.

1. INTRODUCTION

The unrelenting progress of industry and urbanization has resulted in significant damage to the environment, including pervasive pollution of soil, water, and atmosphere with dangerous materials. Heavy metals are particularly problematic among these pollutants because of their toxicity, persistence, and tendency to bioaccumulate. Heavy metal buildup in soils not only reduces fertility but also seriously jeopardizes ecosystem integrity and human health. This problem has sparked a concentrated effort to create and improve remediation techniques, with phytoremediation emerging as a viable, economical, and environmentally beneficial solution. Chaoua et al. [1] and Sandeep et al. [2] claim that because of heavy metals' extreme toxicity, they are among the most important environmental issues facing the world today. Numerous human activities, including the use of fertilizers and pesticides, wastewater discharge, the dumping of industrial waste, mining operations, and fuel burning, cause these hazardous materials to build up in soils [3, 4].

Conforming to Nurzhanova et al. [5], in the soils of the South Kazakhstan region, the content of lead exceeds the standard by 1.8 times, while copper, vanadium, and nickel exceed it by 1.4 times, and zinc by 1.2 times. The contamination by these HMs is mainly attributed to gasoline combustion (60%), non-ferrous metal production (22%), and iron, steel, and ferroalloy production (11%). Keeping with the research by Yapiyev et al. [6], grey soils are formed on loess and consist of yellow-brown loam with a clay particle content of 35-40%. They contain carbonates but lack easily soluble salts. The A horizon has a thickness of 15-18 cm and is completely unstructured. Compared to soils in other zones, they exhibit a more homogeneous particle size distribution. Humus content is 1-2%, content of carbonates is 7-8%. The humus content ranges from 1-2%, carbonate content are 7-8%, gross nitrogen content is 0.05-0.1%, phosphorus content is 0.1-0.12%, and the carbon-to-gross nitrogen ratio is approximately 6-6.5%. The sum of absorbed bases (calcium and a small amount of magnesium) – 8-10 to 15 mg eq.

According to Harindintwali et al. [7], soil remediation technologies for HM-contaminated soils include physical methods such as surface covering, encapsulation, and burial;

chemical – soil cleaning, solidification, and immobilization; electrical – electrokinetic extraction and vitrification; and biological – phytoremediation and bioremediation. Nnaji et al. [8] in their work reported that in order to extract HM from the soil by remediate plants, the following factors must be taken into account: the choice of species that are not toxic to humans and animals that effectively accumulate HM – sunflower, corn and peas; determination of pollution zones; soil quality control. Bioaccumulation of HM has a certain trend of variability in the properties of the plant in terms of metal absorption: intensive – Cd, Cs, Rb; medium degree – Zn, Mo, Cu, Ni, Pb, As; weak absorption – Mn, Cr, Co; hard-to-reach – Se, Fe, Ba, Te. According to the data of Jia et al. [9], distribution of HM in plants can vary with considerable heterogeneity, because minimum and maximal value of concentrations of gross forms of pollutants differ to 100 times in a range 1-40 mg/kg, connections of Cr – 2-30 mg/kg, Cu – 4-100 mg/kg, Ni – 1-50 mg/kg, Pb – 2-25 mg/kg; B – 2-3000 mg/kg.

Daurov et al. [10] emphasize that phytoremediation, which uses the combined metabolic potential of microorganisms and plants, plays a special role in the release of the arable soil layer from HM. The use of biological methods for soil restoration and purification ensures both environmental safety and economic benefits [11]. According to Atabayeva et al. [12], bacteria such as Agrobacterium, Alkaligenes, Arthrobacter, Azotobacter, Azospirillum, Bacillus, Burkholderia, Brevibacterium, Caulobacter, Chromobacterium, Enterobacter, Flavobacterium, Gluconacetobacter, Klebsiella, Micrococcus, and Pseudomonas are widely used as biofertilizers due to their ability to bind iron, thereby protecting the environment from HM accumulation in the soil, suppressing the development of plant pathogens, and promoting plant growth.

Although many pieces of literature have been written about the harmful effects of heavy metal pollution and the potential for phytoremediation as a sustainable solution, there are still few studies that are specifically focused on a particular region and are adapted to the distinct edaphic and climatic conditions of arid and semi-arid regions like South Kazakhstan. With a focus on the dynamics of copper, nickel, and cobalt accumulation, this study attempts to close this gap by offering a thorough assessment of the phytoremediation capability of seeding peas (*Pisum sativum*) in the grey soils of South Kazakhstan. Through the clarification of these heavy metals' migration patterns within the soil profile, their modes of binding, and the mechanisms underlying their absorption by pea plants, this research provides crucial information that will direct the application of phytoremediation techniques in areas with comparable environmental limitations. The study aims to accomplish the following objectives:

(1) Experimentally identify the gross concentrations of various forms of copper, nickel, and cobalt in the initial and remediated soils.

(2) Examine the main forms of metals in the initial and remediated soils.

(3) Calculate the degree of extraction of metals from contaminated soils by sowing peas and determine the main forms of metals absorbed by the plant.

(4) Evaluate the phytoremediation ability of peas on the studied soils.

2. LITERATURE REVIEW

Physico-chemical treatments showed remarkable speed and efficacy in soil remediation; however, they often come with high costs, labor-intensive procedures, and potential compromises to soil functionality. In contrast, biological approaches offer environmentally friendly solutions and enjoy broad social acceptance but require longer durations for the complete removal of contaminants from soils. Nevertheless, the limitations associated with contaminant types and concentrations, soil characteristics, accessibility to affected areas, and process expenses can be mitigated through the integration of various treatment methods. Notably, the study by Aparicio et al. [13] discusses successful instances where combining physicochemical and biological technologies synergistically enhances pollutant degradation efficiency, surpassing the limitations of each individual approach.

Currently, chemical and physical methods of soil restoration are also widely employed to neutralize pollutants with high efficiency. Chemical detoxification of soils is based on the chemical deposition of heavy metals as a result of placing contaminated soil in a container with a reactive mixture (100 mg/kg of hydrogen sulfide in nitrogen, lime, sodium sulfate, iron oxides, organic carbon) [14]. The advantages of this detoxification are that it is acceptable for soils with various physicochemical properties. As a result of soil cleaning with a chemical reaction mixture, 90% of heavy metals can be fixed. However, a major drawback is that the soil cannot be cleaned in place; it requires collection and transfer to a reactor. Another drawback of chemical methods is the use of various reagents that are not always environmentally safe. Besides, these reagents are quite expensive, which affects the amount of soil that can be remediated in this way. Physical methods, such as heating, consume considerable amounts of energy and are limited in their ability to remediate large quantities of contaminated soil or ground. Both of these methods are highly aggressive and suitable for use in cases where the concentration and hazard of pollutants are extremely high (e.g., oil spills) [15].

In recent years, researchers from many countries have actively discussed a valuable new biological method for decontaminating polluted soil, which offers an alternative to conventional cleaning methods by harnessing the biological productivity of living organisms – bioremediation. Biological methods, particularly phytoremediation, help address two important issues: they are cost-effective and do not require the introduction of special reagents, solutions, or chemicals into the soil (thus avoiding additional pollutants) [16]. Recently, the use of plants, specifically phytoextractors, for ecosystem remediation has become more prevalent. Researchers consider using plants to detoxify soils from heavy metals and radionuclides as promising [17, 18]. Phytoremediation methods are effective in detoxifying large soil areas, gradually removing contaminants while maintaining the soil's structure and properties. Land restoration time is reduced by 3-4 times. The choice of plants is a key determinant of the success of phytoremediation of contaminated sites; hence plants must meet the following requirements in order to be used in phytoremediation: resistance to a wide range of climatic conditions, high biomass production, and the ability to grow on and absorb/accumulate pollutants in contaminated soils.

Although physico-chemical treatments have proven to be remarkably quick and effective in cleaning up contaminated soils, there are often considerable environmental trade-offs associated with their use. Methods like soil excavation, chemical leaching, and thermal desorption have the potential to seriously upset the treated site's ecological equilibrium, with collateral harm to plant, soil biota, and groundwater resources possible [19, 20]. The environmental impact of these procedures is further increased by the employment of harsh chemical reagents and the production of hazardous waste streams [15, 21]. Biological methods, on the other hand, such as phytoremediation and bioremediation, make use of living things' metabolic capacities to provide a more ecologically friendly substitute. By increasing microbial activity and reintroducing organic matter, these methods frequently support the restoration of soil health and have a decreased tendency to damage ecosystems [13]. But biological techniques are usually slower and can be limited by things like the bioavailability of contaminants, the state of the soil, and the remediation agents' tolerance limits [22, 23]. As a result, combining biological and physico-chemical technologies has become a viable tactic that maximizes their complimentary advantages to maximize remediation results while minimizing any potential drawbacks.

Phytoremediation methodology is based on various approaches and depends largely on the assigned objectives. The nature of the pollutant, its concentration, and the soil itself determine the type and variety of phytoremediation technologies available. Modern phytoremediation offers two potential approaches for HM detoxification in soils. The first approach utilizes metal-specific super accumulator plants that selectively remove one or two metals in large quantities [24]. The second method involves highly productive plants that generate large above-ground biomass while accumulating a wide range of HMs at relatively low levels [25]. HM absorption through phytoremediation involves several processes, including phytostabilization, rhizodegradation, phytoextraction, phytodegradation, phytoaccumulation, and phytovolatilization (Table 1).

Table 1. Various phytoremediation processes for HM absorption

Types of Phytoremediation	Phytovolatilization	Phytostabilization	Phytoextraction	Rhizofiltration
Area of application	Volatile pollutants	Mining pollution	Areas with low and medium levels of pollution	Sewage
Mechanism	Evaporation by leaves	Complex formation	Hyper accumulation	Rhizosphere accumulation
Pollutant	Organic/Inorganic	Inorganic substances	Inorganic substances	Organic/Inorganic

To treat soils infected with HM, phytoextraction is mainly used. The essence of this method is as follows: plant roots, along with nutrients, absorb both organic and inorganic substances (including heavy metal ions), which are subsequently transported to the above-ground parts of the plants. The word "phytoextragents" describes compounds made from plants that are used to remove pollutants from soil or other environmental matrices [19]. Phytoextragents should be selected experimentally based on the phytoremediation characteristics of the plants themselves and soil-climatic indicators of the soil area to be remediated. After such treatment of the contaminated object, plant phytomass can serve as a source for HM recovery. The phytoremediating plants are burned, and HM are chemically reduced from the resulting ash. Plant biomass containing zinc and copper can be used as fertilizer for soils deficient in these biologically essential trace elements [26].

In general, phytoremediation, as a method of soil detoxification, is not currently at the forefront of popular technologies for treating contaminated soils due to its limited awareness, limited coverage in the media, and low level of implementation of environmental technologies in practice. However, with further research and development of phytoremediation methods as economically viable and environmentally friendly technologies, it is likely to gain an advantage over physicochemical methods [27-29]. The effectiveness and cost-effectiveness of phytoremediation methods became evident with the discovery of hyperaccumulator plants, which can accumulate toxic elements in their leaves up to 5% of the dry weight, including nickel, zinc, and copper [30]. Hyperaccumulator plants predominantly grow on soils contaminated with heavy metals and accumulate them in their shoots to concentrations 1-3 orders of magnitude higher than the permissible levels in non-hyperaccumulator plants. Common field crops – sunflowers and beans – also act as accumulators [31]. All the available data on the accumulation of heavy metals by plants support the feasibility of modern ecological phytotechnology [32].

The ability of hyperaccumulator plants to withstand in polluted soils, their capacity to absorb and accumulate high quantities of hazardous substances, and their propensity to produce biomass are some of the selection criteria used in this process. Thorough screening procedures, including laboratory analyses, field surveys, and greenhouse experiments, are used to identify these plants. To discover naturally occurring hyperaccumulator species, field surveys are carried out at polluted sites; in contrast, greenhouse experiments are utilized to evaluate the growth and accumulation properties of candidate plants under controlled conditions. Subsequently, laboratory techniques including X-ray fluorescence analysis and atomic absorption spectroscopy are utilized to measure the concentrations of harmful components gathered in plant tissues.

In technological terms, the most important part of plants are roots. They absorb toxically contaminated compounds along with the organic soil [33]. The roots release exudates into the rhizosphere, which, along with intracellular enzymes of the root system, facilitate the primary transformation of toxic compounds in the soil and water [34]. Therefore, factors such as the type of root system (taproot, fibrous) and their branching and surface area in the soil are particularly important for phytoremediation processes [35]. This analytical information allows for the efficient monitoring and optimization of phytoremediation processes. In some cases, the use of monoculture is possible, but studies that have successfully applied mixed cultures or alternation of cultures are also known [36]. Legume plants (such as alfalfa, vetch, lentils, and peas) exhibit higher HM absorption compared to cereal crops. Legumes, regardless of the variety of ecological conditions of landscapes, accumulate HM in greater quantities than cereals. On average, the concentration of HM in legumes is 1.54 times higher than in cereals. However, the increase in the content of different elements in legumes compared to cereals varies. For instance, the concentration of copper, lead, nickel, and chromium in legumes exceeds that of grains by 1.9, 1.73, 3.9, and 4 times, respectively, while zinc, cadmium, and fluorine content exceed grains by 1.3 and 1.1 times, respectively. Legumes have the unusual ability to coexist in symbiotic relationships with rhizobia, nitrogen-fixing bacteria, which improves their ability to absorb nutrients and heavy metals from the soil. Legumes also have larger concentrations of metal-binding proteins, like phytochelatins and metallothioneins, which help to sequester and detoxify heavy metals in their tissues. Furthermore, compared to the fibrous root systems of cereals, the root structure of legumes, which is made up of nodules that harbor nitrogen-fixing bacteria, offers a greater surface area for metal absorption. This characteristic of crops can be utilized in the phytoremediation of heavy metal-contaminated soils, especially in grey soils.

In particular, the use of sowing peas (*Pisum sativum*), a legume plant belonging to the Fabaceae family, is of interest. This annual, cold-resistant herbaceous plant is an essential crop for forage and fodder production, allowing for multiple harvests within a growing season. Culture is of great agrotechnical importance in crop rotation. With its taproot system, peas penetrate deeply into the soil, and their highly branched roots further enhance their capabilities. Peas enrich the soil with atmospheric nitrogen through beneficial microorganisms that develop on their roots [37]. The plant is cultivated, it is a valuable food and feed crop, rich in proteins and carbohydrates. Its seeds are close to meat in terms of protein content and contain a significant amount of starch. Being a strong nitrogen fixer, peas have a positive impact on the yield of subsequent crops.

3. MATERIALS AND METHODS

As an object of the study, two territories of the impact of heavy metals were considered, which differ in multifactorial conditions, including weather-climatic and physicochemical, located in South Kazakhstan, in Almaty and Turkestan regions. For the first territory, soil samples were taken from areas of irrigated agriculture belonging to Budan LLP in the Enbekshikazakh district, located 30 km north of Yesik city. Two sampling sites were chosen: one along the highway and the other at a distance of 1000 m from the first site. The second territory was situated in the zone influenced by the production activities and waste of Yuzhpolimetal JSC in the Abay district of Shymkent megalopolis. The total volume of dumps containing Pb^{2+} and Cd^{2+} ions is 1.8 million tons. The migration dynamics of heavy metals through the soil profile were analyzed based on chemical analyses of soil samples taken at depths of 10, 20, 30, and 40 cm. Reference territories located 8000 m away from the analyzed areas were also selected.

The selection of soils was conducted using the grid sampling method. Site selection criteria included geography, land usage, and potential sources of contamination. It was made possible to identify potential hotspots or regions of concern within the study area and to guarantee representative sampling thanks to these factors. 10 squares size 10*10 m were measured. Approximately 2 kg of soil material were taken from each square. The selection was held from a depth of more than 30 cm. The collected material was placed in a container and delivered to the laboratory. The pH of the soil was measured in two conditions: in salt and water extracts. A standard pH m with a hydrogen electrode was used to determine the pH of soils. The pH of the salt extract was determined as follows. Around 10 grams of prepared soil were placed in plastic cups, and 100 ml of a 1 mol/l KCl solution was added. Solution was stirred on a magnetic stirrer for 2 hours at a speed of 40 rpm. The solution was passed through a filter and the first part of the filtrate was removed and the pH value was measured. To determine the pH of the water extract, approximately 10 grams of soil were placed in plastic cups, and 100 ml of distilled water was added. The contents were stirred on a magnetic stirrer for 1 hour at a speed of 40 rpm, and in the same way, passed through a filter and the pH was measured. A neutral adsorption capacity filter, like a cellulose filter, was used for this study. Since cellulose filters are inert and do not react with the ions in the solution, the pH measurement reliably captures the chemical characteristics of the soil. For the analysis of the main forms and concentrations of heavy metals in the soil, a chemical phase analysis method was used, which involves sequential elution of heavy metals and their subsequent determination using atomic absorption spectrometry. The study utilized a sequential elution scheme for heavy metals established by W. Miller in 1983, as outlined in Table 2.

Table 2. W. Miller's sequential elution scheme

Metal Form	Extractant
Water-soluble	H_2O
Exchange	0.1 n Calcium nitrate
Organic	0.1 M Sodium hydroxide
Co-precipitated with Calcium and Magnesium carbonates	0.1 M EDTA (Ethylenediaminetetraacetic acid), pH=7
Co-precipitated with Manganese hydroxide	0.1 M Hydroxylamine in 0.01 M Nitric acid
Co-precipitated with Iron (III) hydroxide	0.3 M Sodium citric acid in 1 M Sodium hydrogencarbonate

The soil samples were exposed to the designated extractant solution for a specific period of time under carefully monitored circumstances for each extraction phase. After 16 hours of stirring the soil with deionized water, the water-soluble fraction was removed. The residue from the preceding stage was shaken with a 0.1 M calcium nitrate solution for five hours in order to remove the exchange fraction. Next, the residue was processed with a 0.1 M sodium hydroxide solution at 80°C for 6 hours, sometimes stirring, in order to remove the metals associated to organic matter. After that, the residue was shaken for an hour at pH 7 with a 0.1 M EDTA solution to extract any metals that had co-precipitated with magnesium and calcium carbonates. By stirring the residue in 0.1 M hydroxylamine hydrochloride in 0.01 M nitric acid at 50°C for 30 minutes, metals related to manganese oxides were removed. Lastly, to recover metals bound to iron and aluminum oxides, the residue was digested for five hours at 80°C with occasional shaking using a 0.3 M sodium citrate/1 M sodium bicarbonate solution.

The samples were centrifuged in between each extraction, and the liquid supernatant containing the extracted metals was carefully taken for examination. Prior to the subsequent extraction stage, the residue was cleaned using deionized water. In order to achieve a more thorough removal of the targeted metal fractions, agitation or shaking of the soil during the extraction phases increased contact between the soil and extractant solution.

A sample preparation system was used to decompose soil and plant samples. The principle of operation of the installation is based on the use of thermal energy for rapid volumetric heating of samples in sealed containers with the addition of oxidants. Thus, the samples were processed at elevated temperatures (>100°C). The mineralization was held in the mode according to pre-compiled standard. During the entire mineralization process, the pressure and temperature inside the containers were monitored in real-time. When processing the pea seeds and soil in the system, they were introduced into solutions of concentrated nitric and sulphuric acids and hydrogen peroxide. The composition of the reagents and processing conditions were carefully chosen to achieve complete mineralization and decomposition of the solid phase into the liquid phase. After splitting, the solution was brought to the desired volume with distilled water. Processing time is 3 hours. Further, the soil was mechanically processed, cleaned of large stones, dead parts of plants, and crushed. Then, it was dried for 2-3 days. The dried soil was placed in containers for planting pea beans in a volume of ~400 grams per container. A small portion was further dried in an oven to conduct necessary procedures and analyses. Beans of seed peas were planted in the container. A hole was made at a depth of 5-7 cm, and the bean was placed inside and covered with soil material. The seeds underwent pre-sowing preparation, being soaked in water with a small addition of growth activators for a day. The beans were planted on August 27, 2022, and the first watering took place on August 29, 2022 (Monday), followed by regular watering every Monday and Thursday for 2.5 months. Each watering involved 50 ml of distilled water.

The planted beans were cultivated in a greenhouse with added illumination and carefully regulated moisture levels through the regular watering regime. Containers with planted beans were placed in a well-moistened, illuminated place to accelerate the processes of growth and development. Beans were also planted in soils that were selected for the study. The corresponding literature was used to determine the species composition of plants. Plant samples were collected following the route examination method and subsequently processed in laboratory conditions. In mid-November 2022, the leaves and stems were collected, washed with distilled water, and dried. Afterward, the leaves and stems were crushed and analyzed for their gross metal content together. The roots were analyzed separately. To calculate the biological accumulation and translocation factors of metals, the gross content of metals in stems, leaves, and roots of plants were determined. To analyze the heavy metal content in toxicotolerant plant species, X-ray analysis and X-ray electron microscopy JEOL-200 (Japan) were utilized. The obtained results were analyzed by calculating the mean and standard deviation in the range of 0.95>P>0.8. Each measurement was conducted in three replicates, and for improved accuracy, in five replicates. Data processing was performed using a personal computer and Excel software package.

4. RESULTS

Investigations into the migration patterns of heavy metals within the soil profile revealed that approximately 70±5.9% of the total recorded volume of acid-soluble heavy metal forms accumulated within the 0-10 cm soil horizon. The concentration of heavy metals in the lower 10-20 cm and 20-40 cm horizons accounted for approximately 45±3.7% and 200±2.1% of the total established volume of heavy metal ions, respectively. Heavy metal content within permissible concentration limits was observed at a depth of 50-60 cm. Thus, the obtained data indicate that the highest concentration of heavy metal ions in the arid climatic conditions of Southern Kazakhstan is found in the upper soil layer up to 40 cm, which largely corresponds to the subtropical steppe zone. When analyzing the flora in the Turkestan region exposed to heavy metal pollution, approximately 103 plant species from 17 families were identified, covering about 96.7% of the investigated soil area. These areas include the following plant communities: the family of grasses (*Gramineae*) – 22 species, 32.9%; the family of compound flowers (*Compósitae*) – 14 species, 16.5%, the genus of legumes (*Fabaceae*) – 10 species, 18.7%; the genus Ipomoea (*Ipomoeaceae*) – 7 species, 6.2%; the genus cabbage (*Brassica*) – 5 species, 5.1%, buckwheat family (*Polygonaceae*) – 4 species, 4.2%; nightshade (*Solanaceae*) – 3 species, 3.1%. The slight increase in heavy metal content in the soil has a weak impact on the overall phytocenosis composition, but visually, it can be observed that the projected coverage of some plant species decreases and is suppressed.

The plant communities in different zones of soil pollution differed in species diversity and phyllosphere composition. In the control zone with the least toxic load (less than 6 Maximum Permissible Concentrations (MPC)), herbaceous plants predominated. However, as the toxicity gradient increased, the proportion of invasive and shrubby species increased. In the same direction, perennial plant species prevailed. At the control site, the share of annual species accounted for 53.5±5.6%, but their value gradually decreased with increasing toxic load. The proportion of annual herb species varied from 37.4±3.4% to 5.2±0.4% at different levels of toxicity. The fall of annual species greatly simplified the cenotic composition of the plant community in pollution-affected zones. The nature of changes in the phytocenotic composition of the plant community and the projected soil coverage is presented in Table 3.

Table 3. Influence of different soil toxicity levels on phytocenotic composition of plant community and projective soil coating

No.	Total Content of Heavy Metal Ions (MPC)	Decrease in the Proportion of Annual Plant Species	Reduction of Projective Soil Cover with Vegetation	Ecological Group and Life Form of Dominant Plant Species
1	1-10	18.9±1.3%	13.6±1.2%	The proportion of eosinophilic and ruderal ecological groups of plants increases
2	50-70	32.3±3.1%	36.5±3.5%	Ruderal and eosinophilic plant groups dominate the plant community
3	More than 200	47.3±4.7%	46.8±4.6%	85±5.8% of phytocenosis occupy perennial xerophytic groups of plant species

The decline in seed reproduction processes among annual species, coupled with the considerable simplification of community composition, has a notable impact on the vegetative projective cover of soil. Consequently, a considerable portion of the affected area remains unvegetated, facilitating wind erosion and the dispersion of dust particles containing high concentrations of heavy metals. Experimental findings on the phytoremediation potential of *Pisum sativum* seeds are provided in Tables 4-8.

Table 4. Mobile form of metals in the initial soils

Soil Type	pH	Mobile form of Metal, mg/kg						
		Cu	**Zn**	**Rb**	**Kd**	**Cr**	**Ni**	**Co**
Sample 1	8.3	35.2	19.2	8.1	0.53	0.23	6.5	5.7
Sample 2	8.5	9.8	5.6	3.2	-	-	1.7	1.3
MPC, mg/kg		3	23	-	-	6	4	5

The data in Table 4 show that the acidity level in soil samples 1 and 2 is 8.3-8.5. This indicates that according to the generally accepted pH level scale, the soil under study can be attributed to alkaline soils. In soil samples 1 and 2, the copper content exceeds the MPC. In sample 1, heavy metals – nickel and cobalt also exceed the MPC. Zinc, lead, cadmium, and chromium in soil samples are within the MPC. The results of the examination of toxic elements distribution in % of the gross content by the main forms of binding in soil samples (W. Miller's scheme of rational analysis) are presented in Table 5. It follows from the table data that the water-soluble form of all toxic elements in sample 1 was higher than in sample 2. The proportions of the organic form of copper, lead, nickel, and cobalt in sample 1 are 27.11; 29.47; 22.96 and 33.05%, and in sample 2 are higher, respectively, 42.39; 41.88; 31.48, and 40.6%. The form of zinc co-precipitated with carbonates Ca and Mg in soil sample 1 is 24.8%, and in soil sample 2 – 20.77% of the total content. In soil sample 1, cadmium and chromium are co-precipitated with Mn(IV), Fe(III), SiO_2, and Al_2O_3 hydroxides, with percentages of 20.11%, 8.15%, and 10.26%, respectively. However, in soil sample 2, there is no binding of toxic elements observed at all.

Table 5. Proportions of various forms of binding of toxic elements

Forms of Toxic Elements			Water-Soluble	Exchange	Organic	Co-Precipitated with Calcium and Magnesium Carbonates	Co-Precipitated with Manganese (IV) Hydroxides	Co-Precipitated with Iron (III) Hydroxides	Co-Precipitated with Silicon Dioxide and Aluminum (III) Oxide
The proportions of various forms of binding of toxic elements in soil samples, %	Cu	Sample 1	11.3	23.10	27.11	12.41	4.65	8.47	12.96
		Sample 2	9.13	16.67	42.39	10.15	3.32	6.47	11.87
	Zn	Sample 1	5.5	42.39	21.13	24.8	19.88	5.45	6.95
		Sample 2	5.05	12.94	32.44	20.77	18.05	4.97	5.78
	Pb	Sample 1	5.84	13.69	29.78	16.07	13.53	11.06	10.03
		Sample 2	5.45	11.23	41.88	12.07	10.53	9.06	9.78
	Cd	Sample 1	6.48	8.75	20.45	25.8	20.11	8.15	10.26
		Sample 2	-	-	-	-	-	-	-
	Cr	Sample 1	13.72	16.8	26.37	16.11	8.45	4.23	14.32
		Sample 2	-	-	-	-	-	-	-
	Ni	Sample 1	6.97	9.05	22.96	24.43	19.78	7.89	8.92
		Sample 2	4.95	7.56	31.48	21.87	18.97	7.14	8.03
	Co	Sample 1	12.63	19.37	33.05	13.75	11.21	3.54	6.45
		Sample 2	10.11	17.25	40.6	12.67	10.03	3.23	6.11

Table 6. Proportions of various forms of nickel (II) in the soil

Metal Form	Proportion of metals, %			
	Sample 1		Sample 2	
	Initial	Remediated	Initial	Remediated
Water-soluble	6.97	5.2	4.95	3.9
Exchange	9.05	8.8	7.56	6.5
Organic	22.96	26.4	31.48	35.9
Co-precipitated with Calcium and Magnesium carbonates	24.43	26.5	21.87	25.05
Co-precipitated with Manganese (IV) hydroxides	19.78	23.1	18.97	22.58
Co-precipitated with Iron (III) hydroxides	7.89	-	7.14	-
Co-precipitated with Silicon dioxide and Aluminium (III) oxide	8.92	-	8.03	-

Tables 6-8 present the results of the investigation of various forms of nickel, cobalt, and copper in the initial and remediated soil samples. The data presented in Table 6 allow concluding that after the remediation of soils, the proportions of metals in soils are changed. Due to a decrease in the initial soils of the water-soluble and exchangeable form of metals in remediated soils, the organic form, co-precipitation with $MgCO_3$ and $CaCO_3$, co-precipitation with $Mn(OH)_2$ increased in the total proportion of metals.

From the data presented in Table 7, it can be seen that the water-soluble, exchangeable, organic forms of cobalt in both samples of the initial soils were on average higher by 2.45, 4.5 and 3.76%, respectively, then in the remediated samples.

Table 8 shows the changes in the proportion of various forms of copper in the samples of initial and remediated soils. The water-soluble, exchangeable form of metal in remediated soils decreased in both samples. The organic form of metal and processes of co-precipitation with $Mn(OH)_2$, $Fe(OH)_3$, SiO_2 and Al_2O_3 in remediated soils increased. Co-precipitation with $MgCO_3$ and $CaCO_3$ in remediated soils increased in sample 1, and decreased in sample 2.

Table 7. Proportions of various forms of cobalt (II) in the soil

Metal Form	Proportion of Metals, %			
	Sample 1		Sample 2	
	Initial	**Remediated**	**Initial**	**Remediated**
Water-soluble	12.63	10.9	10.11	6.94
Exchange	19.37	16.5	17.25	11.12
Organic	33.05	29.7	40.6	36.42
Co-precipitated with Calcium and Magnesium carbonates	13.75	16.6	12.67	16.91
Co-precipitated with Manganese (IV) hydroxides	11.21	17.2	10.03	18.6
Co-precipitated with Iron (III) hydroxides	3.54	-	3.23	-
Co-precipitated with Silicon dioxide and Aluminium (III) oxide	6.45	-	6.11	-

Table 8. Proportions of various forms of copper (II) in the soil

Metal Form	Proportion of Metals, %			
	Sample 1		Sample 2	
	Initial	**Remediated**	**Initial**	**Remediated**
Water-soluble	11.30	7.3	9.13	7
Exchange	23.1	14.53	16.67	14
Organic	27.11	40.5	42.39	45.9
Co-precipitated with Calcium and Magnesium carbonates	12.41	12.95	10.15	8.2
Co-precipitated with Manganese (IV) hydroxides	4.65	9.3	3.32	9.7
Co-precipitated with Iron (III) hydroxides	8.47	8.99	6.47	10.7
Co-precipitated with Silicon dioxide and Aluminium (III) oxide	12.96	13.4	11.87	12.5

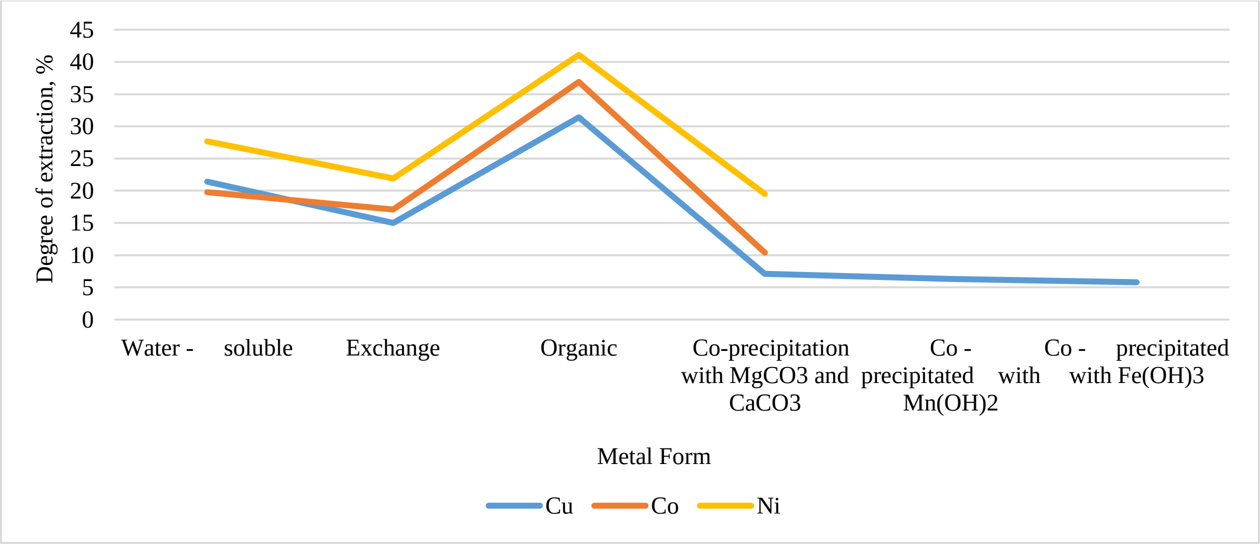


Figure 1. The degree of extraction of various forms of metals in the remediated soil (sample 1)

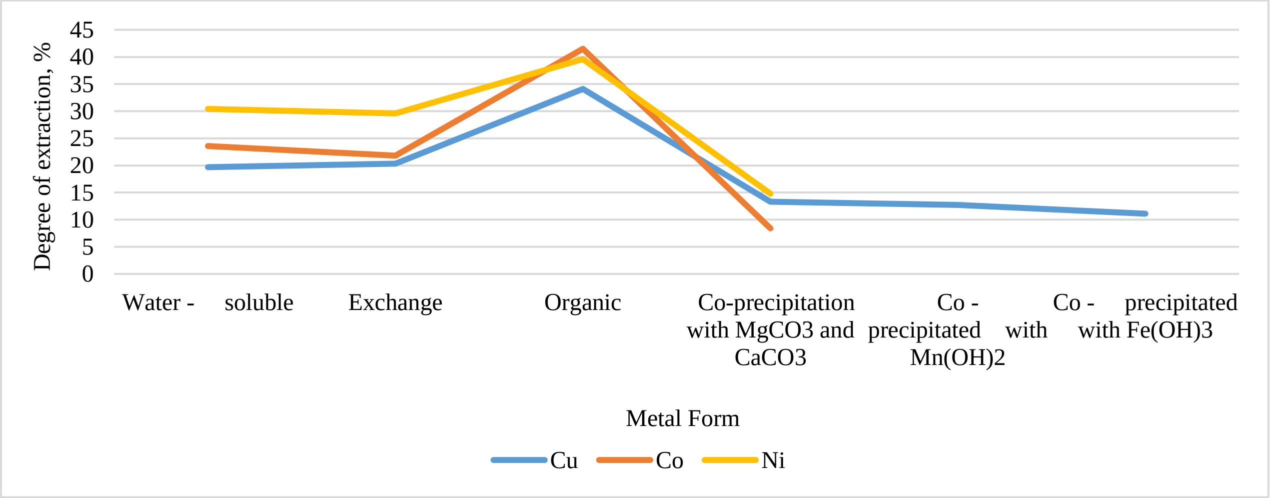


Figure 2. The degree of extraction of various forms of metals in the remediated soil (sample 2)

Figures 1 and 2 show the degree of extraction of various forms of metals in the remediated soils.

Experimental data show that all the studied metals are more absorbed by plants bound by organic components of soils and, primarily, humic compounds (humic acids, fulvic acids, tannins). For each of the several metals under investigation, the remediation procedure' effectiveness was different. The observed decreases in the water-soluble and exchangeable forms of nickel, along with the accompanying increases in the organic and co-precipitated forms, indicate a noteworthy reduction in the metal's bioavailability and capacity for uptake by plants. Because they immobilize nickel and lessen its toxicity, these modifications may have a good effect on soil quality. But in the case of cobalt, the organic form was still significantly prevalent even though the water-soluble and exchangeable forms showed significant decreases. This suggests that remediation may not have been as successful in lowering the metal's total bioavailability. The findings show a clear change in copper towards organic and co-precipitated forms, which may indicate less mobility and plant absorption and improve soil quality. However, additional research using complementary analyses and long-term monitoring is necessary to determine the degree to which these modifications result in better soil health and decreased phytotoxicity. Table 9 presents the results of a study on the gross metal content in the roots of seed peas.

Table 9. Gross metal content in the roots of seed peas

Soil Type	**Metal Content, mg/kg**		
	Cu	**Co**	**Ni**
Sample 1	22.36	28.9	26.4
Sample 2	23.5	31.6	29.6

From the data presented in Table 9 it can be seen that in the soil of sample 1, the content of copper is 22.36 mg/kg, cobalt – 28.9 mg/kg, nickel – 26.4 mg/kg. In the soil of sample 2, the metal content was higher: copper by 1.14 mg/kg, cobalt by 2.7 mg/kg, nickel by 3.2 mg/kg. The accumulation of heavy metals in various parts of plants' vegetative organs is a well-known principle attributed to their protective mechanism at the organizational level. This trend is also observed in the total lead ion content within the biomass of vegetative plant parts, where it decreases from the roots towards the generative organs. For instance, in the Eastern plant species (*Dodartia orientalis*), the concentrations of lead ions were found to be 45.3±2.3, 19.3±0.8, 4.7±0.2, 3.4±0.1, and 0.3±0.01 mg/kg in the root, stems of the first and second orders, leaves, and fruits, respectively. The highest accumulation of lead ions, constituting 62.1±2.5% of the total established volume by chemical analysis, occurs in the root biomass. In comparison, the stems of the first and second orders account for 26.4±1.2% and 6.3±0.2%, respectively, which are significantly lower by 57.3±2.2% and 89.6±4.7% compared to the root biomass. The lowest content was established in the biomass of leaves and fruits. The established principle was confirmed by the results of microanalysis conducted on an electron-raster microscope (Figure 3).

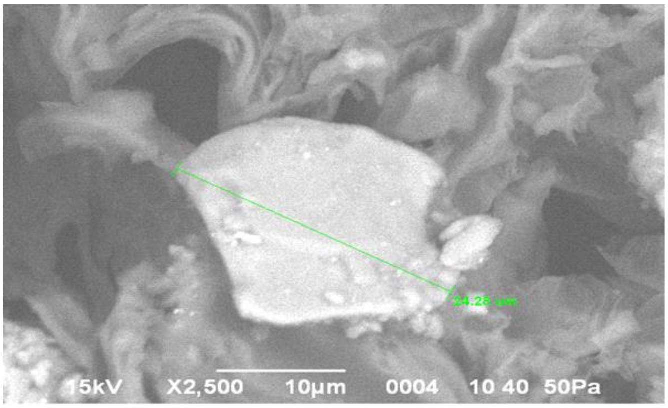
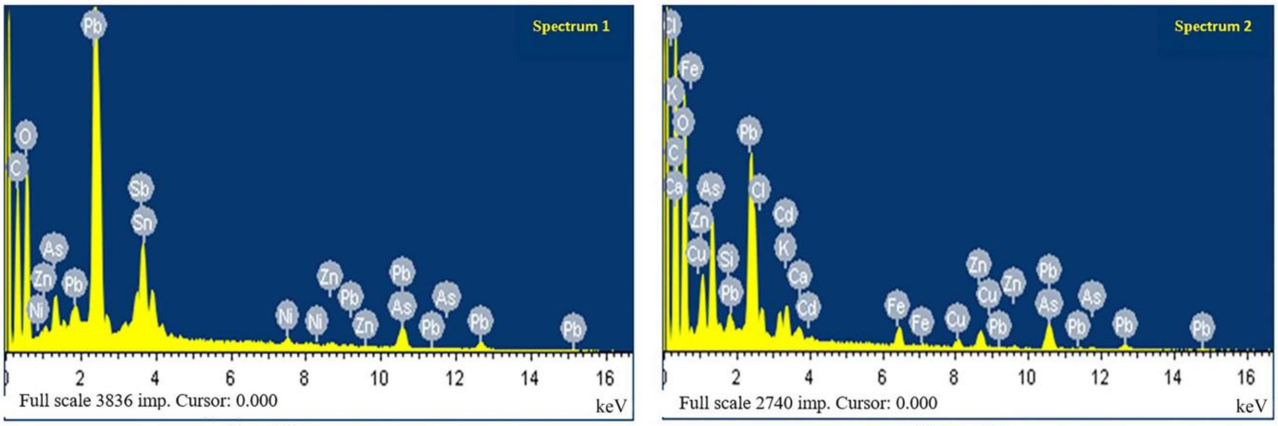


Figure 3. Lead-containing salts in root and stem tissues of *D. orientalis*

The electron microscope image illustrates that lead ions within the biomass of *D. orientalis* are enclosed in substantial conglomerates consisting of insoluble salts derived from organic acids. These formations, ranging from 10-75 nm in size, correspond to the volume of multiple cells within the main tissue. It appears that these salts initially formed in the intercellular space and gradually expanded as neighboring cell walls allowed the formation of localized clusters. The highest concentration of lead ions, with a specific gravity of 30.11% and 26.98%, is observed in salt deposits located in the main root and second-order stem tissues, respectively (Figure 4).



a) root tissue

b) stem tissue

Figure 4. Infrared spectrum peaks and the specific gravity of the main elements of salt deposits of *D. orientalis* plant tissues
Note: a) O – 27.15; Ni – 0.91; Zn – 0.82; As – 2.48; Sn – 4.26; Sb – 10.39; Pb – 30.11; b) O – 22.98; Na – 1.92; Si – 0.46; S – 5.22; Cl – 2.63; K – 2.67; Ca – 3.72; Cu – 1.45; Zn – 1.28; As – 4.08; Pb – 26.98.

For the first-order stem, this indicator is set in the range of 14.45-15.52%. This indicates heterogeneity and the complex chemical nature of salt formation composition. However, the varying specific gravity of lead ions in different parts of plants does not serve as an indicator of the total volume of lead ion migration within the plant. In this regard, the results of chemical analyses are more indicative and reflect its dynamics more reliably (Table 10).

Table 10. Biological accumulation (BAF) and translocation factors (TF) for seed peas

Soil Type	Cu		Co		Ni	
	BAF	**TF**	**BAF**	**TF**	**BAF**	**TF**
Sample 1	3.21	2.51	4.15	1.02	2.63	2.94
Sample 2	3.64	2.64	4.48	1.12	2.19	2.86

Table 10 yields data for the BAF and TF, which shed light on the mobility of metals in seed peas and their possible application in phytoremediation or biomagnification techniques. A BAF value greater than 1 shows that the metal is being accumulated in the plant tissues. Here, the BAF values for Cu^{2+} and Ni^{2+} are more than 1, indicating a buildup of these elements in the plant tissues. Metal translocation inside the plant is indicated by TF, where values larger than 1 indicate active translocation of metals from roots to shoots. Cu^{2+} and Ni^{2+} have TF values above 1 in this study, indicating that they have moved from roots to stems and leaves. On the other hand, cobalt has low TF values, suggesting that it remains in the roots. The varying patterns of accumulation and translocation seen in these metals indicate possible variations in the mobility and absorption mechanisms of these elements within the different plant species. Knowing these dynamics is essential for creating efficient phytoremediation plans, in which plants are used to extract and concentrate metals from contaminated soils, or for determining the possibility of biomagnification, in which metals build up and become more concentrated throughout the food chain. The obtained data allow asserting that the decrease in the total volume of heavy metal ions accumulated in tissues in the direction from the root to the generative organs is associated with the action of various mechanisms for protecting the studied plant species.

The results of this study have significant ramifications for managing soil health and agricultural operations, especially in areas where heavy metal pollution is an issue. This study creates new opportunities for the long-term restoration of polluted soils by proving the effectiveness of phytoremediation methods, particularly the use of sowing peas (*Pisum sativum*) for the extraction of heavy metals like copper, nickel, and cobalt. Traditionally, physicochemical methods have been the mainstay of soil remediation efforts. While these methods are efficient, they can be costly both in terms of money and environmental impact. The sensitive soil ecosystem can be upset and its long-term production compromised by the use of chelating chemicals, excavation, and off-site treatment. Phytoremediation, on the other hand, uses plants' innate ability to absorb and immobilize heavy metals to provide a more gentle and economical method.

The development of focused phytoremediation techniques can be aided by the study's insights into the mechanisms by which heavy metals are accumulated by pea plants, particularly the function of organic molecules and co-precipitation processes. Contaminated agricultural fields could be progressively returned to productive use by choosing plant species with high accumulation potential and modifying soil additives to improve metal bioavailability. Moreover, the results concerning the movement patterns of heavy metals in the soil profile have consequences for actions related to soil management. Farmers and land managers can execute targeted remediation initiatives, concentrating resources on the most severely affected soil horizons, by determining the depth at which heavy metal concentrations peak. This focused strategy maintains the structural integrity and biological variety of uncontaminated soil layers while maximizing the effectiveness of phytoremediation.

5. DISCUSSION

The impact of human activities on the natural environment is increasing day by day and has reached a critical level, leading to fundamental and often irreversible changes in all components of the biosphere. This disruption affects the material and energy cycles, which are the foundation of the dynamic equilibrium and stability of the biosphere. Today, environmental problems pose such vital issues for humanity as the quality of air, water, soil, and food. Soil, being the main medium for the accumulation of heavy metals, receives pollutants from surface runoff, groundwater, rocks, and the atmosphere [38, 39]. Major factors negatively affecting the physicochemical properties of soil are the overall toxicity of hydrocarbons, pesticides, and HM salts [40]. In polluted soils, the availability of nutrients necessary for plant growth decreases, affecting the germination and yield of plants [41]. Utilization of HM in soils is a very laborious process since they are not decomposed but simply redistributed between various components of the natural environment.

The mobility and migration of heavy metals in the soil are influenced by several soil-ecological factors, such as humus content, presence of organic and inorganic ligands, soil colloids, soil pH acidity, granulometric and mineral composition, soil density, and the prevailing acidic, alkaline, or redox conditions in the soil environment. The distribution of macro- and microelements and the forms of HM occurrence vary with the depth of the soil cover. The main factors influencing this process are the mechanical composition of the soil, acidity, phosphorus and organic matter content. Neutral soils tend to retain metals better than acidic ones, yet metal sorption mainly occurs in alkaline conditions. The soils of Southern Kazakhstan are primarily grey or light chestnut soils, characterized by moderate alkalinity. The increased content of HM in soils is a favorable factor for their transition to plant organisms. According to Boluspayeva et al. [42], in soils little affected by economic activity, the content of heavy metals is insignificant, the approximate amount of cadmium is 0.13 mg/kg, mercury – 0.08 mg/kg, lead – 16 mg/kg, copper – 20 mg/kg, nickel – 40 mg/kg, cobalt – 8 mg/kg, chromium – 100 mg/kg, iron – 8000 mg/kg.

Increased concentrations of heavy metals are concerning in areas that are only mildly impacted, but things get much worse in places where there is a lot of industrial activity, mining, and uncontrolled waste disposal. Comparing such severely contaminated soils to baseline values seen in pure environments, studies have shown startling increases in heavy metal contents. According to Han et al. [43], studies carried out in the area of abandoned mining sites have revealed lead concentrations that are up to 50 times higher than the allowable limits. Additionally, levels of zinc and cadmium have been found to exceed regulations by factors of 25 and 15, respectively. In some extreme cases, such as the areas surrounding the Aznalcollar mine spill in Spain, mercury concentrations in affected soils have been recorded at levels a staggering 1,000 times higher than in uncontaminated soils [44]. These concerning numbers demonstrate the catastrophic effects of unchecked industrial activity on soil quality and the pressing need for efficient remediation techniques to reduce the hazards to ecological systems and public health.

Elevated concentrations of HM are found in landscapes as a result of various human activities, such as the use of fertilizers, discharge of wastewater from industrialized cities, and the application of metallurgical slag for soil liming [45]. According to Bian et al. [46], soil enrichment with zinc can occur through systematic use of organic fertilizers. Uranium, thorium, and radium can enter plants through phosphorus mineral fertilizers and from the atmosphere in areas with significant coal combustion. Stable strontium enters the landscape with simple superphosphate and phosphogypsum [47, 48]. Noticeable environmental contamination with copper is observed in regions with intensive vineyard cultivation, where this element is widely used to combat diseases affecting these crops. The study provides data on phytoremediation of heavy metals using field peas, a fast-growing annual legume that can produce 2-3 crops in a single growing season. According to Popek et al. [49], there are many herbaceous species capable of thriving in conditions of high anthropogenic pollution during the natural establishment of organic reservoirs. Some of these species include *Melilotus officinalis (L.) Pall., Trifolium hybridum L., Trifolium repens L., Trifolium pratense L., Vicia cracca L., Medicago sativa L., Sonchus arvensis L.,* and *Chamerion angustifolium (L.)*. These plants possess specific properties that make them suitable candidates for use as phytoremediation extractors on polluted soils.

The growing environment of the remediating plants has a major impact on the phytoremediation processes' efficiency. The bioavailability and mobility of heavy metals are significantly influenced by the pH of the soil, with slightly acidic to neutral pH ranges often favoring enhanced metal uptake by plants. Certain species, such as *Medicago sativa* and *Melilotus officinalis*, have been shown to accumulate heavy metals optimally in soils that have a pH of 6 to 7.5. Another important consideration is the moisture condition of the soil, since water stress can hinder plant development and nutrient uptake. The majority of the herbaceous plants listed are able to flourish in soils that have good drainage and moderate moisture content, usually between 60% and 80% of field capacity [50]. Additionally, temperature affects the rates at which heavy metals are absorbed by plants and their metabolic activities; in general, warmer temperatures promote these processes. On the other hand, too much heat can cause physiological stress and stunt plant growth, indicating that there may be temperature optimalities unique to certain species.

In the arid conditions of Turkestan and Almaty regions, toxic substances tend to accumulate in the upper layers of the soil, where the processes of movement are much slower than in a temperate climate. As a result, the high toxicity of the processed soil layer hinders the growth and development of the root systems of annual plants and significantly reduces the reproductive capacity of seeds. Phytoremediation, using mechanisms of phytoextraction and phytostabilization, is a promising method for extracting heavy metal ions from contaminated soils. According to Khan [51], the hyperaccumulating properties of certain plants, which allow them to accumulate heavy metals in their vegetative parts and transport ions from the soil to various plant parts, represent one of the most prospective phytoremediation technologies. It was established that in the arid climatic conditions of the subtropical climate of Southern Kazakhstan, the highest concentration of heavy metal ions is in the upper layer of soil up to 40 cm deep.

As noted by Yan et al. [27], many plants with hyperaccumulation of heavy metals grow slowly and have low biomass, which limits their use for the phytoremediation of heavy metal-contaminated soils. During the process of plant stabilization, heavy metal ions are absorbed and retained in the roots and rhizosphere, thereby suppressing the mobility of these ions, limiting their leaching into groundwater, and reducing their bioavailability for transfer into the food chain. This helps lower dietary exposure and lessen the health dangers that come with it. This is especially crucial for communities living in areas impacted by mining or industrial activity that depend on locally grown vegetables and subsistence farming. By using phytoremediation to reduce the number of heavy metals that enter the food chain, we can protect sensitive populations like pregnant women and children, as well as improve the quality of food and provide a safer environment for farming and human consumption. Methods of soil purification from toxic components using phytoextraction are based on growing plants in a polluted environment. The phytoextraction process is most effective when cleaning soils from the accumulation of nickel, zinc, and copper [52]. Heavy metals accumulate in the root system and above-ground parts of plants until reaching maximum concentrations of toxic substances over several cycles of growing crops in contaminated soil. Subsequently, the plants are incinerated, and the ash is stored in hazardous waste disposal sites. Some plants accumulate significant amounts of metals in their root systems and soil masses: cobalt, copper, chromium, lead, and nickel are present in quantities exceeding 1000 mg/kg, and manganese and zinc are present in quantities exceeding 10 g/kg on an absolutely dry basis, making them suitable for metal-producing ores [53].

The results of the study on the content of different forms of nickel, cobalt, and copper in the initial and post-remediation soil samples indicate the process of soil reclamation, as the proportion of heavy metals has decreased. The addition of chelating organic preparations and co-precipitation with manganese carbonates and hydroxides reduced the overall percentage of heavy metals in the reclaimed soil due to decreased water solubility and exchange capacity of the metals. According to Kowalik et al. [54], plants assimilate mobile and water-soluble forms of HM. Organic components of soil, such as humic compounds like humic acids, fulvic acids, tannins, and flavonoids, play a crucial role in the uptake of heavy metals by plants. Nickel enters plants in the form of nickel humates and its biological role involves incorporation into the structural organization and functioning of nucleic acids DNA and RNA, and protein molecules. Nickel is also part of the urease enzyme, which aids in urea decomposition. Copper is absorbed by plants in the form of exchangeable and water-soluble compounds and serves as a regulator of metabolic processes, participating in the synthesis of growth inhibitors, water exchange, and the redistribution of substances, it is also involved in enzymes that enhance the ability of plants to withstand frost, heat, and drought. As per Alrawiq et al. [55], cobalt in plants is contained in ionic and complex form. Its main function is to participate in atmospheric nitrogen fixation, stimulate the development of plant tissues, increase the number of ribosomes, and enhance the mobility of bacteroids in the root nodules of leguminous plants. Cobalt also stimulates cell proliferation in leaves by increasing mesophyll tissue.

6. CONCLUSIONS

Based on the experimental data obtained, toxic-tolerant plant species of both native flora and a number of crops are promising for use in phytoremediation purposes. Among these, legumes such as alfalfa, vetch, lentils, and peas are distinguished due to their higher capacity for absorbing HM compared to grain crops. On average, the concentration of HM in legumes is 1.54 times higher than in cereals. This feature of crops can be used in the phytoremediation of grey soils contaminated with heavy metals. In particular, the use of sowing peas (*Pisum sativum*), which belong to the (*Fabacae*) legume family, is of interest – this annual cold-resistant herbaceous plant is an indispensable crop. The culture is of great agrotechnical value in crop rotation. Its root system allows for deep penetration into the soil. Experimental studies on the phytoremediation capacity of sowing peas showed changes in the forms of metals in remediated soils. The water-soluble and exchangeable forms of metals decreased, while the organic forms and co-precipitation with minerals like $MgCO_3$, $CaCO_3$, and $Mn(OH)_2$ increased. The study also revealed that peas are accumulators of copper, nickel, and cobalt, with the main forms of metal absorption being organic, water-soluble, and exchangeable.

Regarding the migration dynamics of heavy metals in the soil profile, approximately 70±5.9% of the total established volume of acid-soluble forms of heavy metals accumulate in the 0-10 cm soil horizon. The concentrations in the lower 10-20 cm and 20-40 cm horizons amounted to 45±3.7% and 20±2.1% of the established total volume of heavy metal ions, respectively. The content of heavy metals in the soil, within the MPC values, was established at a depth of 50-60 cm. The impact of different levels of soil toxicity on the phytocenotic composition of the plant community and the projected soil cover was investigated. In the arid conditions of Turkestan and Almaty regions, there is a tendency for toxic substances to accumulate in the upper soil layers, where migration processes occur at a slower rate compared to moderate climates. Therefore, the high toxicity of the treated soil layer hinders the growth and development of root systems in annual plants, considerably reducing their reproductive ability. The loss of annual species greatly simplifies the cenotic composition of the plant community of impact pollution zones. The identified pathways of heavy metal migration within plants, along with the quantitative and qualitative characteristics of metal accumulation, will enable the prediction of the effectiveness of phytoremediation measures.

The overall guidelines for phytoremediation with peas and the observed migration patterns of heavy metals might apply to other locations, but the precise quantitative results concerning metal accumulation, affected soil depths, and phytocenotic shifts might differ in areas with diverse environmental circumstances. Further research is needed to see whether these findings can be extended to areas with varying soil types, levels of precipitation, temperatures that may influence the behavior of heavy metals and plant response.

In areas affected by heavy metal contamination, the effective use of phytoremediation methods has important ramifications for human health and the environment. Phytoremediation can assist restore the health of terrestrial ecosystems by gradually lowering the amounts of heavy metals in soils, which will allow a wider variety of plant and animal species to flourish. In agricultural areas, where cleaning up contaminated fields improves the safety and quality of food crops, this is especially crucial. Reducing the number of heavy metals in soils can improve human health by reducing the risk of the intake of contaminated produce, accidental soil ingestion, and dust particle inhalation. As children are particularly susceptible to the neurodevelopmental effects of heavy metals, lowering the environmental burden on them safeguards a vitally important group of people. In areas where heavy metal pollution from natural or industrial sources is a problem, phytoremediation offers a long-term, affordable, and environmentally responsible solution to enhancing environmental quality and protecting human health.

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