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Geochemical and Agroecological Problems of Irrigated Soils in Central Fergana

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Abstract

The article analyzes the biogeochemical problems of irrigated soils with varying degrees of salinity. In particular, it provides a comprehensive discussion of the composition, structure, and geochemical characteristics of biogeochemical barriers formed as a result of the development of arzik–shokh and shokh–arzik horizons in irrigated meadow–saline soils of the Central Fergana region. In addition, within the group of radial barriers, two-sided (bipolar) barriers are distinguished, and the geochemical as well as physicochemical differences between their upper and lower parts are scientifically characterized. The research findings indicate that the processes and properties occurring in the upper part of the horizon differ significantly from those observed in its lower part, confirming the complex nature of matter and element migration within the soil profile.

Keywords: barrier, arzik–shokh, migration, accumulation, pedolith, ecological.

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1 Introduction

At present, the comprehensive investigation of the agrochemical, chemical, physical, and biogeochemical properties of irrigated soils, as well as the study of the migration, accumulation, transformation, and geoenergetic characteristics of chemical elements within soil composition, constitutes one of the pressing scientific challenges at the global level. An in-depth analysis of these processes is of significant importance for assessing soil fertility, ensuring ecological sustainability, and scientifically evaluating anthropogenic impacts.

The distribution of heavy metals and radioactive elements within different horizons of the soil profile manifests through processes of accumulation or migration at various depths, depending on their physicochemical properties, the granulometric composition of the soil, its physicochemical parameters, and hydrogeological conditions. These processes occur in an interconnected manner and collectively shape the system of biogeochemical problems observed in irrigated soils.

2 Literature Review and Methodology

The Central Fergana Desert was formed in the course of historical–geological development as an accumulative territory where rivers, streams, and flood flows originating from surrounding areas, particularly from mountain slopes, converged and deposited sediments. During this process, the deposition and accumulation of transported sedimentary materials proceeded continuously over many centuries.

Depending on the flow velocity and the intensity of floods, the granulometric (mechanical) composition of the deposits changed over time and became stratified across different layers. Owing to the limited outflow of water from the area and the high-temperature, arid climatic conditions, the major portion of water was expended through evaporation. As a result, the area functioned as an erosion base, where clayey materials, sands, and water-soluble salts accumulated in varying quantities and proportions within different horizons of the soil profile [3].

The role of mineralized groundwater located close to the surface in the occurrence of these processes has been scientifically substantiated, and it has been emphasized that these waters were under considerable pressure [12, 13]. The genetic characteristics, chemical and mineralogical composition, and meliorative properties of the soils in this region were investigated by M.A. Pankov (1957), G.I. Olovyanishnikov (1937), A.N. Rozanov (1941), and others [8, 9, 12].

The hydromorphic nature of the Central Fergana soils was substantiated by M.A. Pankov (1957), who was among the first to emphasize the presence of dense gypsum-accumulated and arzik-horn-like layers in soil profiles located at the marginal parts of alluvial fan cones.

In his research, M.U. Umarov examined the influence of different types of agricultural crops on the physical and physicomechanical properties of Central Fergana soils and noted the existence of compacted, water-impermeable layers at depths of 70–120 cm, which, in turn, adversely affect the physical properties of the soil [13].

According to the data of P.N. Besedin (1979, 1981), the soils of the Quvasoy alluvial fan are characterized by salinization, waterlogging, poor permeability, the presence of arzik features, and horn-like formations.

Research Methods. Based on field observations, our investigations established that soils of this type are still present in several districts of the region, and soil samples were collected from these areas. In the course of the study, integrated (comprehensive) scientific methods were employed.

In particular, geochemical approaches developed by V.I. Vernadsky and A.Ye. Fersman [1] were applied. These methods are based on the study of migration processes of chemical elements within the Earth's crust and its various spheres, including the pedosphere. In analyzing pedogeochemical processes from a geochemical perspective, systematic methodological approaches proposed by A.I. Perelman and M.A. Glazovskaya were also utilized.

The chemical composition of soil and water samples, soil humus content, the composition of exchangeable cations, the content of gypsum, calcium and magnesium carbonates, as well as the total and mobile forms of nitrogen, phosphorus, and potassium were determined according to generally accepted methodologies. In particular, methodological guidelines of the Uzbekistan Cotton Research Institute (SoyuzNIXI, 1973) and the procedures described in "Guidelines for the Chemical Analysis of Soils" developed by Ye.V. Arinushkina (1970) were used.

The research object can be schematically represented as follows (Figure 1) [3].

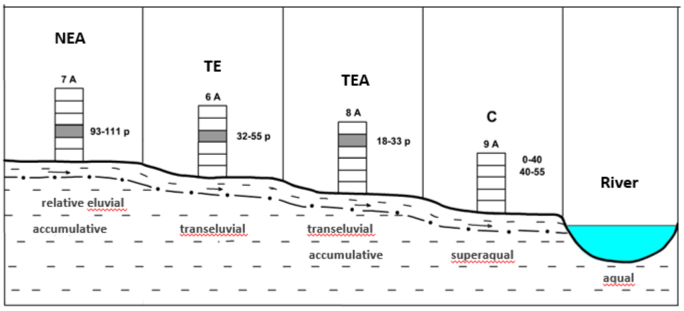
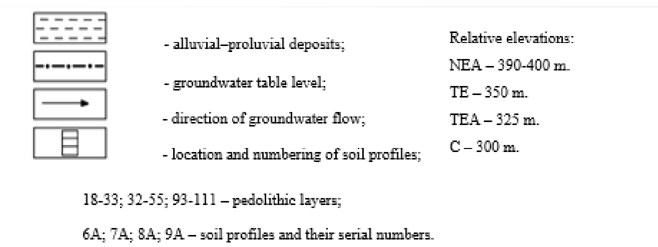


Figure 1. Schematic representation of a closed-type landscape-geochemical profile.



3 Results and Discussion

It is well known that in the processes of accumulation and migration, the chemical and physical properties of elements—such as ionic radius, the number and configuration of electrons in the outer electron shell, charge magnitude, ionization potential, and others—play a significant role.

According to Beus et al. [2], isomorphic substitution of elements in primary minerals influences their migration behavior.

In soils and their genetic horizons, a number of geochemical barriers are formed under the influence of various factors, and these barriers constitute the basis of biogeochemical problems.

The soils of Central Fergana have developed on alluvial, alluvial–proluvial, and other types of deposits, which differ from one another in terms of genesis and composition [6, 7, 10].

In the irrigated meadow saz soils of Central Fergana, the formation of arzik-horn-like and horn-arzik layers has led to the emergence of biogeochemical barriers. According to the data of G. Yuldashev, A. Turdaliev, and others, these layers have formed at various depths within irrigated soils and have been designated as pedolithic soils [3].

The concept of geochemical barriers was introduced into science by A.I. Perelman [4], who classified barriers within soil layers—such as neoformations, salt accumulations, and similar features—as microbarriers.

In studying the processes of element migration and accumulation, the significance of geochemical barriers developed by A.I. Perelman is considerable; they are understood as zones where the intensity of chemical element migration sharply decreases over short distances, resulting in an increase in their concentration [6].

Certain neoformations formed within the soil likewise perform the role of pedogeochemical barriers for specific groups of elements or individual elements.

The soils of Central Fergana included in the present study are irrigated meadow saz soils, characterized by distinct dense, cemented layers occurring at various depths within their genetic horizons. The depth of the dense cemented layer increases from south to north, approaching closer to the soil surface (Figure 1). Variations in the thickness of this layer are also observed [3].

In some cases, this regularity is disrupted, and such deviations are associated with the structure of the soil cover, microrelief, and the degree of drainage of the area. These soils are mainly characterized by evaporative, oxygen, gley, sorption, and bidirectional carbonate–gypsum and gypsum–carbonate barriers, among others.

According to the theory of A.I. Perelman, in evaporative barriers a number of water-soluble salts accumulate in a specific sequence. Such barriers are characteristic of the studied soils, where the concentration of salts occurs in the following order: $MgSO_4 > CaSO_4 > Na_2SO_4 > NaCl > Ca(HCO_3)_2$.

In evaporative barriers, in addition to certain groups of cationogenic and anionogenic elements, macroelements, microelements, lanthanoids, and radionuclides are concentrated in varying amounts. However, this phenomenon has been scarcely investigated in irrigated soils and agricultural crops.

From this perspective, a number of properties and characteristics of the soils of Central Fergana were comprehensively studied. The pedolithic horizons of the investigated soils, representing gypsum–carbonate barriers, are located at depths of 18–32 cm, 32–55 cm, and 93–111 cm and are characterized by dense arzik-horn-like and horn-arzik compositions (Figure 2). Although the thickness of these layers is not considerable, they are capable of performing a barrier function. These barriers were designated as (S–Ca) gypsum–carbonate and (Ca–S) carbonate–gypsum barriers [3].

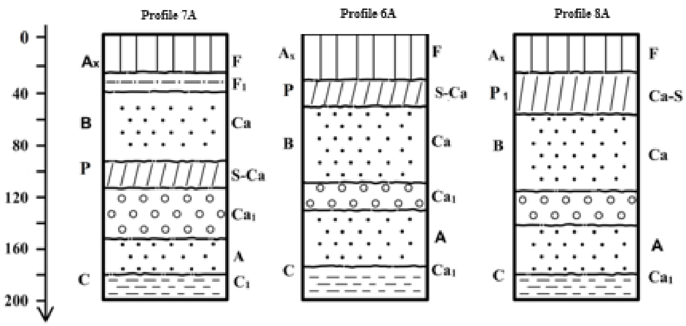


Figure 2. Schematic representation of a pedogeochemical barrier.

Pedogeochemical barriers:
F_1; F – evaporative barriers;
S-Ca – arzyk-shokh;
Ca-S – shokh-arzyk;
Ca – carbonate;
Ca_1 – slightly carbonate;
A – oxygen barrier;
C_1 – gley barrier.

Conventional symbols:
A_h – plow layers;
P – pedolith, arzyk-shokh;
P_1 – pedolith shokh-arzyk;
B – carbonate-accumulating layer;
C – parent material composed of alluvial–proluvial deposits.

It is known that bidirectional barriers were distinguished by A.I. Perelman, who classified as bidirectional those lateral barriers in which one side—that is, the entry side of the barrier—is acidic while the exit side is alkaline, and vice versa [3].

In our investigations, bidirectional barriers were identified within the group of radial barriers; these formed within the internal horizons of the soil during the process of soil formation. They are based on the distinction between upper and lower parts, whereby the properties of the upper portion of a layer differ from those of its lower part (Figure 3) [11].

We describe radial barriers as follows:

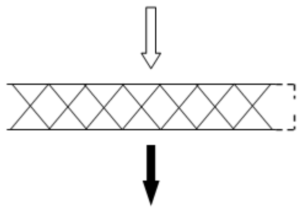


Figure 3. Representation of radial bidirectional barriers.

1. – direction of chemical elements toward the barrier;
2. – direction of chemical elements beyond the barrier;
3. – accumulation of elements within the barrier;

m_1 – state of the medium before the barrier;

m_2 – state of the medium after the barrier;

H – barrier thickness.

Perelman designated the change in geochemical indicators along the pathway of chemical element migration as the barrier gradient. The condition we propose likewise retains the term *barrier gradient*; however, instead of L (barrier length), H (barrier thickness) is adopted, which results in a minor modification of the formula, namely

$$C_1 = \frac{m_1 - m_2}{H};$$

C_1 – barrier gradient; H – barrier thickness.

Thus, in certain cases, a number of changes can be observed in bidirectional barriers formed in this manner. Under conditions of such bidirectional (bipolar) barriers, specific morphological and geochemical alterations are occasionally manifested.

The morphological characteristics of these barriers consist in their radial formation and their occurrence at various depths within irrigated meadow saz soils. Within these horizons, the migration of elements and substances proceeds in two directions—both from top to bottom and from bottom to top—indicating the presence of complex matter exchange processes within the soil profile.

In the studied soils, these barriers are characterized by a dense arzik–horn-like composition. Moreover, I.P. Gerasimov [5] proposed the term "pedolith" to describe dense neoformations with distinct horizons composed of iron, carbonate, and gypsum that are formed during soil development. It is precisely within these barrier layers that carbonate and sulfate salts of calcium and magnesium accumulate in certain quantities.

The obtained data indicate that the irrigated meadow saz soils are carbonate- and gypsum-bearing. In these soils, the total carbonate content ranges from 6.1 to 18.8%, $CaCO_3$ from 4.5 to 16.2%, $MgCO_3$ from 4.3 to 16.10%, gypsum from 3.5 to 44.1%, and epsomite from 2.2 to 27.2%.

Particular attention should be paid to the fact that the highest contents of carbonate and sulfate salts correspond to the arzik–horn-like and horn–arzik layers (Profile 8A: 18–33 cm; 6A: 32–55 cm; 7A: 93–111 cm). As a result of the accumulation of carbonate and sulfate salts, as well as certain elements, these layers have become highly compacted, leading to reduced water and air permeability and significantly impeding the migration of elements and substances between the upper and lower horizons.

In the soils of Profile 9A, the contents of gypsum, carbonates, and epsomite are distributed relatively uniformly; however, a somewhat higher concentration is observed in the 55–89 cm layer. This indicates the presence of a residual former low-permeability horizon as well as a carbonate illuvial layer. Considering the longer period of cultivation of the soils of Profile 9A, their well-developed drainage condition, and the influence of advanced agrotechnical practices, it can be concluded that the existing dense layer is gradually diminishing over time.

The barriers described above also possess certain positive aspects in agricultural practice. When applying mineral and organic fertilizers and irrigation water to agricultural crops, and taking into account the depth of such layers, it becomes possible to reduce the total annual rates of fertilizers and irrigation water by 20–30% compared to soils where such barriers are absent.

Table 1. Content of lanthanoids and radioactive elements

Profile No.	Depth, cm	Content, 10^{-4} %									
		La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Th	U
7A	0–28	12,8	19,4	8,80	1,3	0,28	0,19	0,77	0,084	4,40	11,8
	28–36	12,1	19,2	10,4	1,5	0,40	0,18	0,92	0,091	5,2	17,7
	36–93	3,1	15,26	2,2	0,9	0,78	0,15	0,83	0,024	2,1	2,4
	93–111	19,4	15,3	7,2	1,2	0,90	0,27	0,77	0,071	3,7	3,5
	111–150	22,8	34,1	17,1	2,6	0,64	0,35	1,5	0,16	8,3	5,8
	150–180	20,8	31,6	19	2,7	0,57	0,32	1,5	0,15	8,8	16,5
6A	0–22	26,9	41,9	20,0	3,1	0,87	0,43	1,8	0,19	10,6	7,3
	22–32	29,6	44,3	20,9	3,7	0,77	0,43	1,9	0,20	9,9	5,6
	32–55	28,8	43,4	24,8	3,8	0,88	0,49	1,9	0,29	10,9	4,4
	55–80	21,8	34,4	16,8	3,1	0,70	0,38	1,6	0,16	8,6	4,3
	80–140	22,1	38,5	16,6	3,3	0,78	0,41	1,6	0,17	8,4	3,9
	140–200	23,3	35,5	16,4	2,8	0,66	0,33	1,7	0,16	8,9	3,7
8A	0–18	51,9	70,8	35,9	6,3	1,3	0,72	2,8	0,31	20,9	6,9
	18–44	58,1	73,7	38,8	6,8	1,7	0,74	2,5	0,39	28,8	6,9
	44–83	51,4	67,7	26,4	6,7	1,2	0,68	2,8	0,32	25,7	6,4
	83–121	38,0	53,3	13,9	4,5	1,0	0,53	2,2	0,24	12,9	4,5
	121–157	37,6	51,8	17,1	4,7	1,1	0,55	2,3	0,27	12,6	4,0
	157–202	38,0	54,2	27,9	4,8	1,0	0,54	2,2	0,26	14,2	4,4
9A	0–40	33,7	45,8	14,7	4,6	0,81	0,48	1,8	0,21	14,0	4,5
	40–55	31,4	43,9	15,8	3,9	0,79	0,47	1,9	0,21	15,6	4,3
	55–89	35,0	47,4	15,0	4,0	0,81	0,48	1,8	0,20	14,0	4,4
	89–143	38,3	54,6	17,5	5,1	0,93	0,60	2,4	0,28	14,8	4,3
	143–212	39,1	55,8	19,1	5,7	0,87	0,68	2,5	0,28	14,9	4,8
Vinogradov clarke		29	70	37	8	1,3	4,3	0,33	0,8	13	2,5

Chemical elements contained in soils migrate within soil horizons and the surrounding environment and, in most cases, accumulate in particular genetic layers of the soil.

The agroecological condition of lands depends, among other factors, on both the distribution and the concentrations of elements belonging to the lanthanide group within landscape units, particularly in soils.

According to data on the contents of elements such as La, Ce, Nd, Sm, Eu, Yb, Tb, Lu, Th, and U within the genetic horizons of the irrigated meadow soils of Central Fergana, differences in their quantitative indicators are observed throughout the horizons extending from the plow layer to the parent material in meadow soils with varying degrees of irrigation.

In particular, the lanthanum content in the plow layers of the studied soils ranges from $12.8 \cdot 10^{-4}$ % to $51.9 \cdot 10^{-4}$ %. Considering the entire soil profiles, the minimum value of $3.1 \cdot 10^{-4}$ % corresponds to the 36–93 cm layer of Profile 7A, whereas the maximum value of $58.1 \cdot 10^{-4}$ % is observed in the 18–44 cm layer of Profile 8A. Similar patterns can also be identified for other elements.

According to the total indicators, the highest content corresponds to cerium. The average concentration of this element within the soil horizons was observed to be $43.12 \cdot 10^{-4}$ %.

The content of neodymium is also considerable; in irrigated meadow saz soils it was determined to be $18.36 \cdot 10^{-4}$ %. The concentrations of the remaining lanthanide elements range from $0.11 \cdot 10^{-4}$ % to $4.5 \cdot 10^{-4}$ %, from samarium to lutetium.

The quantitative indicators of naturally occurring radioactive elements such as thorium are likewise not high in the studied soils, varying from $4.8 \cdot 10^{-4}$ % to $16.3 \cdot 10^{-4}$ %.

Uranium, in general, was found to occur in amounts exceeding the lithospheric clarke. Its highest concentrations were recorded in newly irrigated meadow–takyr soils compared to other soil horizons, reaching $11.2 \cdot 10^{-4}$ % in the 75–92 cm layer of Profile 24A. The obtained data indicate that the highest concentrations in almost all horizons correspond to Ce, whereas the lowest values are characteristic of Lu.

Based on the numerical data obtained from the analytical results, background concentrations of the studied elements were established for irrigated meadow–takyr and meadow saz soils and were expressed in the form of geochemical spectra.

Background concentrations of lanthanoids and radionuclides for meadow saz soils, 10^{-4} %:

$$\underset{43.12}{\mathrm{Ce}} > \underset{30.43}{\mathrm{La}} > \underset{18.36}{\mathrm{Nd}} > \underset{12.4}{\mathrm{Th}} > \underset{6.49}{\mathrm{U}} > \underset{3.79}{\mathrm{Sm}} > \underset{1.83}{\mathrm{Yb}} > \underset{0.81}{\mathrm{Eu}} > \underset{0.45}{\mathrm{Tb}} > \underset{0.20}{\mathrm{Lu}};$$

Background concentrations of lanthanoids and radionuclides for meadow–takyr soils, 10^{-4} %:

$$\underset{45.59}{\mathrm{Ce}} > \underset{26.0}{\mathrm{La}} > \underset{18.0}{\mathrm{Nd}} > \underset{8.3}{\mathrm{Th}} > \underset{5.6}{\mathrm{U}} > \underset{2.8}{\mathrm{Sm}} > \underset{1.49}{\mathrm{Yb}} > \underset{0.68}{\mathrm{Eu}} > \underset{0.43}{\mathrm{Tb}} > \underset{0.15}{\mathrm{Lu}}[9]$$

For microelements, background values characteristic of meadow saz soils were calculated and are presented as follows. Background, mg/kg:

$$\underset{114.12}{\mathrm{Ni}} > \underset{46.5}{\mathrm{Cr}} > \underset{11.32}{\mathrm{As}} > \underset{8.25}{\mathrm{Co}} > \underset{7.3}{\mathrm{Sc}} > \underset{6.39}{\mathrm{Cs}} > \underset{4.27}{\mathrm{Sb}}$$
$$> \underset{3.8}{\mathrm{Hf}} > \underset{2.98}{\mathrm{W}} > \underset{0.91\text{–}0.92}{\mathrm{Br, Ta}} > \underset{0.56}{\mathrm{Cd}} > \underset{0.28}{\mathrm{Hg}} > \underset{0.0012}{\mathrm{Au}}$$

Table 2. Ecological assessment of irrigated meadow soils

Name of elements	Total REE content, mg/kg	Irrigated meadow saz soils		Irrigated grassland-barren soils [9]	
		Content, mg/kg	Degree of ecological risk	Content, mg/kg	Degree of ecological risk
Antimony	4.5	4.27	0.95	1.48	0.33
Nickel	20	144.12	7.21	30.50	1.53
Arsenic	2	11.32	5.66	11.75	5.88
Cobalt	5	8.25	1.65	7.42	1.48
Zinc	55	81.49	1.48	67.80	1.23

The laboratory analytical results obtained for the determined concentrations of chemical elements in the studied soils were processed in accordance with the maximum permissible concentrations (MPC) and hazard classes of the elements. Based on these criteria, the investigated irrigated meadow–takyr and meadow saz soils were ecologically assessed, and the results are presented in the following table (Table 3, Figure 4).

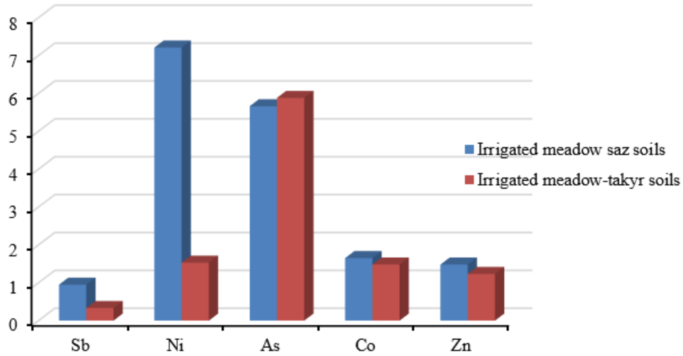


Figure 4. Degree of ecological risk of irrigated soils

Based on the table data, it can be noted that the ecological risk levels of the irrigated meadow soils were determined according to the concentrations of nickel, arsenic, cobalt, and zinc.

Table 3. Ecological assessment of soils

Levels of soil contamination	Integrated pollution indices	Degree of ecological risk					Sum
		Sb	Zn	Co	Ni	As	
Permissible	1–8	0,95	1,48	1,65	7,21	5,66	
Slight	8–16						
Moderate	16–32						16,95
Strong	32–64						
Very strong	64–128						

In this case, the highest degree of ecological risk in meadow saz soils corresponds to nickel, with a value of 7.21, followed by arsenic (5.66), cobalt (1.65), and zinc (1.48) in decreasing order. With respect to antimony, both soil types fall within the ecologically safe category, with respective values of 0.95 and 0.33.

In irrigated meadow–takyr soils, the highest ecological risk index corresponds to arsenic, with a value of 5.88, followed by nickel (1.53), cobalt (1.48), and zinc (1.23) in decreasing order [9].

This condition—namely, the arzik–horn-like pedolithic horizons representing gypsum–carbonate barriers—may appropriately be classified, according to their depth of occurrence within the soil profile, as surface, shallow, and deep pedolithic radial barriers.

Systematic monitoring of the content of chemical elements in irrigated soils, together with their migration processes, accumulation patterns, and other geochemical characteristics, is of considerable importance for assessing and monitoring the agroecological status of irrigated territories. These processes provide a necessary theoretical and practical basis for preventing desertification, salinization, contamination, and other adverse ecological phenomena in soils, as well as for scientifically substantiating reclamation measures.

According to the results of the study, the investigated irrigated meadow–takyr and meadow saz soils belong to the ecologically safe category. Continuous monitoring of soil cover conditions, the implementation of comprehensive scientific and applied research, and the development of measures aimed at improving soil fertility based on these findings constitute essential tasks. At the same time, the development and practical implementation of effective agroecological and agromeliorative measures to prevent contamination by lanthanoids, heavy metals, and metalloids will create opportunities for achieving stable, high, and high-quality crop yields.

4 Conclusion

Today, conducting monitoring of irrigated soils, scientifically and practically investigating the properties of chemical elements, and identifying their migration, accumulation, and differentiation play an important role in improving soil fertility as well as enhancing the yield and quality of crops.

Based on the results obtained in this study, it becomes possible to develop agroecological and agromeliorative measures aimed at preventing the contamination of irrigated soils and cultivated plants with heavy metals and metalloids, thereby ensuring the production of environmentally clean agricultural products.

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Data Availability Statement: Data supporting the report's findings can be found here.

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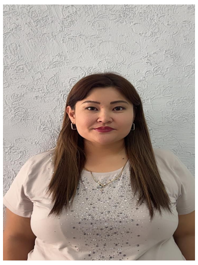

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