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BIOGEOCHEMICAL FEATURES OF SOILS AND VEGETATION IN THE AREA OF THE ATOMIC LAKE OF THE FORMER SEMIPALATINSK NUCLEAR TEST SITE

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KEY WORDS

Semipalatinsk Nuclear Test Site, Atomic Lake, elemental composition, radiation contamination, soil analysis, vegetation, biological absorption coefficients, biogeochemical characteristics.

ABSTRACT

This article presents the results of a comprehensive study on the elemental composition of soils and vegetation in the area of the Atomic Lake, located within the Semipalatinsk Nuclear Test Site. The main objective of the research was to assess the concentrations and distribution patterns of chemical elements in soils and local plant species, with a particular focus on understanding the biogeochemical characteristics shaped by prolonged anthropogenic impact and radiation exposure. Fieldwork was conducted to collect representative samples of soil and vegetation, which were subsequently analyzed in the laboratory using modern analytical techniques. The obtained data underwent thorough statistical processing to identify distribution patterns of elements and to examine the relationships between elemental concentrations in soils and their uptake by plants. A comparative analysis was carried out between the concentrations of trace elements in the studied plants and those in a reference plant species. Additionally, the concentrations of trace elements in the soils were compared with the Clarke values of the upper continental crust. Special attention was given to the calculation of biological absorption coefficients, which provided valuable insights into the ability of different plant species to selectively accumulate elements. These coefficients enabled the evaluation of adaptive mechanisms developed by vegetation in response to chronic radiation stress. The findings highlight the significance of biogeochemical research for assessing environmental risks associated with nuclear contamination.

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1. INTRODUCTION

Wide-scale nuclear tests conducted at the Semipalatinsk test site had a major impact on the ecological and radiological conditions of the region. One such locations is the Atomic Lake created as a result of the underground nuclear explosion in 1965. This artificial reservoir is of particular interest for research due to its impact on ecosystems [1, 2].

In the studies of scientists M.R.Aktayev, S.N.Lukashenko, A.O. Aidarkhanov et al., the Institute of Radiation Safety and Ecology of the National Nuclear Center of the Republic of Kazakhstan, all the main aspects of radiation contamination of the Atomic Lake and its impact on the environment were studied thoroughly. These studies identified that the major portion of radionuclides at the Atomic Lake was accumulated in the soil pile resulted from the soil displacement after the nuclear explosion. The specific activity of man-made radionuclides in the pile soil is 4000 Bq/kg of241Am, 15000 Bq/kg of137Cs, 17000 Bq/kg of239 + 240Pu, 10000 Bq/kg of90Sr, 65000 Bq/kg of3H, 20000 Bq/kg of152Eu and 13000 Bq/kg of154Eu [3, 4, 5].

Studies conducted by M.R. Aktayev et al. showed that radionuclide contamination of the coastal waters of the Atomic Lake had the following values: 3H varied from 100 to 1500 Bq/kg, 90Sr - from 1 to 3 Bq/kg, and 137Cs and 239+240Pu were below 0.03 and 0.002 Bq/kg. They

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made a conclusion that this contamination is associated with the leaching of radionuclides from the soil and groundwater from the wells of the Balapan site [6]. The authors also studied the elemental composition of water both in the Atomic Lake itself and in the Chagan River. The evidence suggests that the waters in the Atomic Lake influence zone exceeds average contents in comparison with natural waters for such elements as strontium, lithium, iron and uranium [7, 8, 9].

The problem of the effects of nuclear tests on ecosystems remains relevant to this day. In addition to radiological contamination, which has been the focus of previous research, considerable attention should be paid to non-radiative effect, including changes in the chemical composition of the environment, anthropogenic transformation of soils and alteration of trophic chains. Nuclear explosions and further processes caused a change in the natural soil profile, increased erosion processes and a decrease in organic matter. These changes lead to deterioration of soil fertility and limitation of the ability of ecosystems to self-regeneration [10].

In addition, technogenic factors contribute to changes in the migration of chemical elements in soil and plant systems, which affect their distribution and bioaccumulation in vegetation [11]. The study of the elemental composition of plants on the territory of the Atomic Lake located on the territory of the former Semipalatinsk Nuclear Test Site enables a deeper understanding of the dynamics of accumulation and distribution of elements in ecosystems that have undergone technogenic changes. The analysis of these processes is important for assessing the long-term condition of soils and green cover, as well as for developing actions for the rehabilitation of exposed areas.

The scientific novelty of the study is a deep analysis of the elemental composition of soil and plants near the Atomic Lake, with a focus on changes caused not only by radionuclide contamination, but also by adverse environmental conditions. Unlike previous studies, which focused mainly on the migration of radionuclides, this study reveals outstanding differences in the macro- and microelement composition of soil cover and vegetation in the areas affected by nuclear exposure and in the control zone.

The practical relevance of the research is the need to take these factors into account when predicting recovery processes in the Atomic Lake ecosystem. The results obtained make it possible to clarify the dynamics of soil transformation caused by man-made impacts and their impact on biodiversity. In this way, the study contributes to understanding the long-term effects of nuclear testing, going beyond the typical analysis of radiation pollution and offering a new perspective on ecosystem degradation under extreme conditions.

The goal of the research: to research the elemental composition of soils and plants in the zone of influence of the Atomic Lake.

2. MATERIALS AND METHODS

The study area is located within the Balapan site of the former Semipalatinsk Nuclear Test Site and is characterized by an arid continental climate, sparse vegetation covers and technogenically transformed soils [12]. The soils are predominantly light-textured, weakly developed, with low organic matter content and show signs of mechanical disturbance caused by underground nuclear explosions and subsequent erosion processes [13]. In this research, the elemental composition of soils and plants was studied at 2 sampling areas near the Atomic Lake. At present, the Atomic Lake is a closed artificial water body surrounded by embankments of varying height and width. These embankments consist of blocks and fragments of rocks of different origins, as well as loose unconsolidated material containing both fine detrital particles and soil components. The zonal soil type in the area is represented by light chestnut soils [14,15]. The study area experiences a strongly continental climate, characterized by significant seasonal and diurnal temperature variations. Summers are typically hot and moderately dry, whereas winters are cold and snowy. January minimum temperatures range from −27 °C to −33 °C, while July maximum temperatures reach +32 °C to +37 °C [16].

The sample area No. 1 – "Outer Lake" is located on the territory of the outer lake, where no radioactive contamination was observed. The sample area No. 2 – "Atomic Lake" is located on one of the shores of the Atomic Lake. A schematic map of the sampling site is shown in Figure 1, which was built using the QGIS program. The survey of the selected areas and sampling was conducted in September 2023.

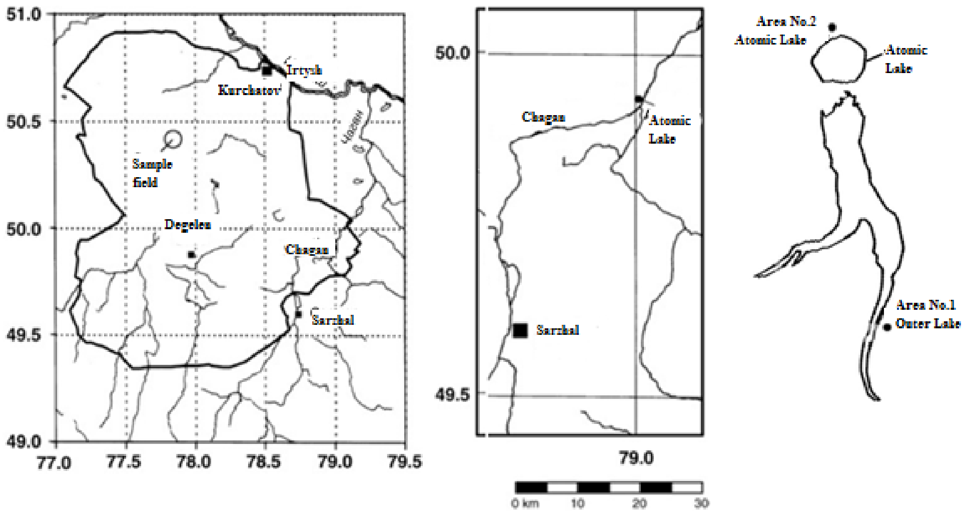

Figure 1. Schematic map of sample areas

Soil was sampled using the envelope method at a depth of 0-50 cm in accordance with GOST 17.4.4.02-84 [17]. The taken samples weighing at least 1 kg were dried in a drying oven at a temperature of 105 °C for 3-6 hours, following which they were packed and sent to the laboratory.

The plants were sampled according to GOST 588-2019 using a square sampling, each square sized 1 by 1 meter [18]. In each square, all plant species that could be found within the research area were sampled.

The following species were sampled at area No.1: california sagebrush Artemisia californica L.; wormwood Artemisia absinthium L.; stinking fleabane Dittrichia graveolens L.; weak sedge Carex supina L.; common reed Phragmites australis L.; tamarisk french Tamarix gallica; hollow-stemmed asphodel Asphodelus fistulosus; gmelin's sea lavender Limonium gmelinii L.; at the area No.2 sampled the following species: common mugwort Artemisia vulgaris L.; sandhill sage Artemisia pycnocephala L.; wormwood Artemisia absinthium L.; weak sedge Carex supina L.; branched gypsophila Gipsophila paniculata L.

The nomenclature of Latin plant species is given according to the reference book by S.K. Cherepanov "Vascular plants of Russia and neighboring countries (within the former USSR)"[19]. For each plant species, three individual specimens were collected and combined into one composite sample. In total, 13 composite plant samples and 10 soil samples from the root layer were analyzed. Each composite sample of plants and samples of soils were analyzed once without analytical duplication. Each species was assembled separately and packaged in labeled bags. Whole plants (aboveground parts and roots) were used for chemical analysis.

The preparation and analysis of samples to determine the concentration of 41 chemical elements of soil and plants was performed according to the NSAM method No. 499, using complete acid decomposition [20]. Elemental analysis was performed using an inductively coupled plasma optical emission spectrometer ICP-OES Agilent 5800 (Agilent Technologies, USA). The measurements were carried out under standard operating conditions recommended by the manufacturer. Analytical wavelengths were selected to minimize spectral interferences. The accuracy of measurements was controlled using certified reference materials, and the relative analytical error did not exceed 5–10% for most elements.

The bioavailability in soils was assessed by the value of the biological absorption factor [21]:

$$\textbf{Biological absorption factor} = C_{plant}/C_{soil} \quad (1)$$

where C_{plant} is the concentration of an element in a plant sample, mg/kg; C_{soil} is the concentration of an element in a soil sample, mg/kg.

The tables used the following abbreviations for statistical parameters: X is the arithmetic mean, Δ is confidence range (p=0,95), RE is relative error of the confidence range as a percentage (p=0,95), Max is maximum value, Cv is variation factor (VF).

Statistical processing of the research results was performed using standard methods [22,23] utilizing the Orange Data Miner and Microsoft Excel software packages. The value of Clark trace elements in the soils of the upper continental crust is shown from [24].

3. RESULTS AND DISCUSSION

In the research the analysis of soil and plant samples was performed to determine the concentration of 41 chemical elements.

The grouping and classification of the identified elements is presented in table 1, which was performed using the World Health Organization document on pollution and toxicity of the elements. [25].

Table 1
Classification of analyzed elements in samples

Group	Element
Metals	Ag, Al, Ba, Be, Bi, Cd, Ce, Co, Cr, Cu, Fe, Ga, Hf, In, La, Li, Mn, Mo, Nb, Ni, Pb, Sc, Sn, Sr, Th, Ti, Tl, U, V, W, Y, Yb, Zn, Zr
Heavy metals	Ag, Ba, Bi, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Sn, Sr, Th, Ti, Tl, U, V, W, Y, Zn, Zr
Macronutrients	Fe, P
Trace elements	Li, B, Al, P, Ti, Cr, Mn, Fe, Co, Cu, Ni, Zn, Ga, As, Sr, Y, Zr, Mo, Ba, La, Ce, Pb
Semi-metals	As, Sb
Non-metals	Se

A data bulk on the content of trace elements in the studied samples was obtained. Statistical indicators were calculated to assess changes in data for different samples, to assess the accuracy of measurements, and to determine how much the content of elements from sample area No. 1 and sample area No. 2 differs from the natural background. Statistical indicators of the content of trace elements in soil are presented in Table 2. This table shows the average concentrations of trace elements in the soil (X), measurement errors (Δ), minimum and maximum concentrations, as well as variation factors, which show how variable the data are relative to their average value (Cv%).

Table 2

Statistical indicators of the gross content of trace elements in the soil of the studied areas, n=10, mg/kg

Element	Outer Lake X±Δ(RE%) min-max(Cv%)	Atomic Lake X±Δ(RE%) min-max(Cv%)	Clarke of the upper continental crust [24]
Li	30,3±4,1(14) 26,4-32,9(11)	25,9±1,3(5) 24,3-27,0(4)	30
B	1,6±0,3(16) 1,3-1,8(13)	0,8±0,6(72) 0,5-1,6(58)	34
Al	90860±11442(13) 79748-103406(10)	101905±4073(4) 98731-106609(3)	76000
P	1090±254(23) 833-1264(19)	938±54(6) 882-997(5)	610
Ti	5346±273(5) 5071-5584(4)	6425±421(7) 6121-6933(5)	3410
Cr	46,2±7,0(15) 40,4-54(12)	78,6±5,5(7) 73,0-84(6)	150
Mn	1575±90(6) 1507-1694(5)	1230±63(5) 1143-1261(4)	670
Fe	78247±9781(13) 69851-86799(10)	91553±2905(3) 89208-94188(3)	40600
Co	27,8±8,9(32) 19,8-35(26)	37,7±1,56(4) 36,5-39(3)	17
Cu	75,3±11,5(15) 61,1-84(12)	94,3±11,9(13) 86,6-109(10)	39
Ni	29,1±5,9(20) 23,8-33(16)	38,9±1,3(3) 37,4-40(3)	62
Zn	129±11,0(14) 105-143(12)	142±7(5) 136-151(4)	78
Ga	15,3±2,7(17) 13,2-18(14)	18,6±1,0(5) 17,8-20(4)	19
As	12,0±10,0(83) 3,7-24(67)	26,6±6,8(26) 19,0-31,1(21)	6,5
Sr	302±31,3(10) 281-344(8)	357±15(4) 340-372(3)	270
Y	14,8±2,27(15) 12,6-17(12)	16,3±0,8(5) 15,3-17(4)	26
Zr	84±19,8(24) 63,8-102(19)	85,4±12,8(15) 75,5-98(12)	160
Mo	0,8±0,4(56) 0,4-1,3(45)	3,9±7,1(184) 1,1-14(148)	1,5
Ba	528±66(13) 468-594(10)	650±307(47) 518-1091(38)	510

Table 2

Statistical indicators of the gross content of trace elements in the soil of the studied areas, n=10, mg/kg

Element	Outer Lake X±Δ(RE%) min-max(Cv%)	Atomic Lake X±Δ(RE%) min-max(Cv%)	Clarke of the upper continental crust [24]
La	21,8±1,2(5) 21-23(4)	22,9±0,9(4) 22-24(3)	32
Ce	40,0±8,3(21) 30,6-48(17)	49±26(52) 34-85(42)	63
Pb	6,2±3,1(49) 2,1-8,3(40)	7,4±2,7(36) 5,6-11(29)	17

The concentrations of most elements in the Atomic Lake are higher than in the Outer Lake, which proves a significant anthropogenic impact. This especially manifests for elements such as Cr, Fe, Cu, Pb and As, where the values in the Atomic Lake significantly exceed the background content. For example, the average Cr content in the Atomic Lake samples is 78.6 mg/kg, while for the Outer Lake it is 46.2 mg/kg. This element, being toxic in high concentrations, is an important indicator of pollution.

When comparing the concentration of trace elements obtained during the research from the Atomic Lake sample area and the concentration of elements in the upper continental crust, differences were found. Increased concentrations were observed in Al and Sr by 1.3 times, P by 1.5 times, Ti, Mn and Zn by 1.8 times, Fe and Co by 2.2 times, Cu and Mo by 2.5 times, As by 4 times.

Elements such as Li, P, and Ti have values close to clarke of the upper continental crust, which may indicate minimal anthropogenic impact on the concentration of these elements in the reservoirs under research.

Thus, increased concentrations of elements in the soil of the Atomic Lake may be the result of long-term anthropogenic effects, in particular, nuclear tests, toxic chemical emissions and radiation pollution, which is reflected in significant deviations from the natural background of these elements.

The data also show that the variation factor for trace elements vary significantly between the soils of the Outer Lake and the Atomic Lake, which indicates differences in geochemical conditions. Outstanding differences are observed for a number of elements, such as B and Mo: in the Atomic Lake, their variation factors reach 58% and 148%, respectively, which indicates the presence of certain differences in the mineral composition of soil. The most stable elements with low variation factor in both reservoirs include Al and Fe, which may reflect their resistance to redistribution under these conditions.

The quantitative content of chemical elements in biological objects and abiotic substances of the environment in the area of the Atomic Lake influence is a key indicator for biogeochemical research.

In this study, the concentrations of Cu, Zn, Mn, and Co in the Atomic Lake soils were 94, 142, 1230, and 38 mg/kg, respectively. In comparison, similar research by A.A. Kirgizbayeva et al. [26] on metal content in soils within the Atomic Lake area of the former Semipalatinsk Test Site reported values of 34, 61, 2200, and 13 mg/kg, respectively. Thus, measured concentrations of Cu and Co were nearly three times higher than those reported by Kirgizbayeva et al. in 2014, while Zn was more than twice as high. In contrast, Mn concentrations were approximately 1000 mg/kg lower than the previously reported values. The elevated levels of Cu, Co, and Zn, alongside the decreased Mn content, indicate a shift in metal accumulation and mobility in the soils of Atomic Lake compared to previous studies, reflecting changes in biogeochemical conditions over time.

Taking into account the different physiological significance of trace elements and the peculiarities of their selective absorption from soils exposed to specific geochemical conditions, the content of these elements in plants varied widely. Table 3 shows the content of trace elements in the composition of vegetation distributed by species diversity in the studied areas and the indicators for the reference plant.

Table 3

The content of the elemental composition of vegetation in the studied areas, mg/kg of air-dry

Element	The Outer Lake								The Atomic Lake					X±Δ(RE%) min-max(Cv%)	Reference plant [27]
	Artemisia californica	*Carex supina*	*Tamarix gallica*	*Limonium gmelinii*	*Artemisia absinthium*	*Phragmites australis*	*Dittrichia graveolens*	*Asphodelus fistulosus*	*Artemisia vulgaris*	*Artemisia pycnocephala*	*Carex supina*	*Artemisia absinthium*	*Gipsophila paniculata*		
Li	0,05	0,4	0,2	0,9	0,4	0,3	1,1	0,3	1,1	1,68	1,0	0,9	1,4	0,73±0,52(71) 0,05-1,68(71)	0,2
B	6,2	53,4	1,0	1,0	14,7	1,0	27,6	1,0	3,3	94,8	38,3	1,0	173,0	51±57(112) 3-173(112)	40
Al	380	274	406	487	548	296	629	463	196	897	580	637	929	517±222(43) 196-929(43)	80
P	831	978	422	1536	962	2296	1440	853	1788	1788	2319	552	1739	1346±627(47) 422-2319(47)	2000
Ti	21	104	40	211	56	80	49	92	147	634	284	228	374	178±173(97) 21-634(97)	5
Cr	4,8	26,8	14,9	8,1	7,2	18,6	7,3	7,9	5,5	83,3	23,7	19,5	63,5	22±24(109) 4,8-83 (108)	1,5
Mn	245	104	53	169	148	156	149	96	138	180	142	144	153	144±45(31) 53-245(31)	200
Fe	819	919	591	1861	930	5676	1123	3526	1362	4812	2585	2134	3087	2264±1614(71) 591-5676(71)	150
Co	0,1	0,6	0,2	0,6	1,1	1,2	1,1	1,1	0,8	3,4	1,7	1,6	2,7	1,2±0,9(75) 0,1-3,4(76)	0,2
Ni	2,8	15,1	9,5	6,7	2,1	20,3	1,9	8,4	2,4	52,6	12,8	10,6	38,3	14,1±15,2(108) 1,9-52,6(108)	1,5
Cu	4,3	3,7	6,0	6,1	5,4	10,8	5,6	15,8	5,3	10,5	6,6	8,8	4,3	7,2±3,4(48) 3,7-15,8(48)	10
Zn	26	41	18	387	32	1375	84	486	44	104	77	64	75	216±377(174) 18-1375(174)	50
Ga	0,1	0,2	0,1	0,4	0,2	0,5	0,2	0,4	0,3	1,0	0,5	0,4	0,6	0,38±0,25(65) 0,12-1(65)	0,1

Table 3

The content of the elemental composition of vegetation in the studied areas, mg/kg of air-dry

Element	The Outer Lake								The Atomic Lake					X±Δ(RE%) min-max(Cv%)	Reference plant [27]
	Artemisia californica	*Carex supina*	*Tamarix gallica*	*Limonium gmelinii*	*Artemisia absinthium*	*Phragmites australis*	*Dittrichia graveolens*	*Asphodelus fistulosus*	*Artemisia vulgaris*	*Artemisia pycnocephala*	*Carex supina*	*Artemisia absinthium*	*Gipsophila paniculata*		
As	0,24	0,12	0,10	0,10	0,48	1,99	0,73	1,13	1,15	0,98	1,21	0,10	0,95	0,9±0,54(61) 0,1-1,99(61)	0,1
Sr	50	27	97	96	88	120	128	74	195	82	48	112	303	109±72(66) 27-303(66)	50
Y	0,19	0,12	0,24	0,21	0,38	0,18	0,29	0,25	0,15	0,63	0,34	0,46	0,48	0,30±0,15(50) 0,12-0,63(50)	0,2
Zr	2,1	1,9	2,8	3,5	3,7	1,8	2,1	2,5	1,9	7,4	3,9	3,5	9,6	3,59±2,36(66) 1,76-9,62(66)	0,1
Mo	0,05	0,05	0,59	0,05	0,42	0,31	0,13	0,14	0,17	0,27	0,47	0,33	0,44	0,26±0,18(68) 0,05-0,59(68)	0,5
Ba	19	17	14	19	18	23	32	23	17	37	32	28	46	25±10(38) 14-46(38)	40
La	0,29	0,26	0,36	0,52	0,48	0,51	0,72	0,38	0,44	1,15	0,70	0,78	0,90	0,6±0,3(45) 0,3-1,1(45)	0,2
Ce	0,7	0,4	1,1	1,4	1,4	1,8	2,0	1,3	2,9	1,1	0,8	1,5	3,1	1,5±0,8(53) 0,4-3,1(53)	0,5
Pb	0,5	1,6	0,7	6,5	1,2	3,0	2,4	2,5	1,0	9,3	3,8	1,5	3,1	2,9±2,5(88) 0,5-9,3(88)	1

Based on the analysis, outstanding differences in the accumulation of trace elements between plants growing in the Outer Lake and the Atomic Lake were revealed.

On the Outer Lake, the maximum concentrations of elements are recorded in the following species:

- In *Phragmites australis* the P content reaches 2296 mg/kg, Zn — 1375 mg/kg.
- In *Dittrichia graveolens* there is a high content of Zn (486 mg/kg) and Cu (15.8 mg/kg).
- In *Tamarix gallica* elevated levels of Fe (591 mg/kg) and Cr (14.9 mg/kg) were recorded.

On the Atomic Lake, the maximum values of trace elements are determined in:

- *Artemisia pycnocephala* — the B content is 94.8 mg/kg, Fe — 4812 mg/kg, Cr — 83.3 mg/kg.
- *Artemisia absinthium* — the Fe content reaches 2134 mg/kg, Cr — 19.5 mg/kg.

Carex supina from the Atomic Lake is characterized by an increased Al content (580 mg/kg), which is 2.1 times higher than that of *Carex supina* from the Outer Lake (274 mg/kg). Cr concentrations in *Artemisia pycnocephala* are 83.3 mg/kg, which is significantly higher than in *Carex supina* from the Outer Lake, where this indicator is 26.8 mg/kg. This indicates a high level of chromium contamination of soil and plants in the territory of the Atomic Lake, which is confirmed by soil sample analysis, which was described in this research earlier.

In *Carex supina*, which grows in the Atomic Lake, the Fe concentration was 2585 mg/kg, which is 2.8 times higher than in *Carex supina* in the Outer Lake, where the iron concentration was 919 mg/kg. These data indicate a high level of iron concentration in vegetation in the Atomic Lake area.

Dittrichia graveolens on the Outer Lake showed a Cu concentration of 5.6 mg/kg, while on the Atomic Lake in *Artemisia absinthium*, the Cu concentration was 8.8 mg/kg, 1.5 times higher. This indicates a higher degree of copper contamination in the Atomic Lake territory.

In *Tamarix gallica*, the concentration of Cr on the Outer Lake was 14.9 mg/kg, while on the Atomic Lake in *Artemisia pycnocephala*, the concentration of Cr reached 83.3 mg/kg, which is 5.5 times higher.

Thus, in plants growing on the Atomic Lake, on average, higher concentrations of trace elements (especially B, Fe, Cr, Ni, Sr) are recorded compared to the Outer Lake, which indicates an outstanding difference in the accumulation of elements depending on environmental conditions. This indicates the effect of radiation and chemical pollution on the ability of plants to selectively accumulate certain chemical elements from the environment, especially from the soil. The concentrations of P, Ti, Sr, Y, and Ba in the Atomic Lake are generally comparable to those in the Outer Lake or even lower. This indicates a less manifested accumulation of these elements in plants, possibly due to their lower mobility in the soil.

A comparison between the concentrations of trace elements in samples from the Outer Lake and the Atomic Lake and its concentrations in the reference plant showed that Al concentrations in the Outer Lake range from 274 to 629 mg/kg, while in the Atomic Lake concentrations of Al range from 196 to 929 mg/kg, while in the reference plant the concentration of Al is 80, which is much lower than the plants from the Atomic Lake and the Outer Lake areas. For Ti, an almost 127-fold excess was found in the *Artemisia pycnocephala* plant of the Atomic Lake compared to the value in the reference plant, which is equal to 5 mg/kg. In general, the most significant differences are observed for a number of trace elements such as: Fe, Cr, Co, Ni, Zn, As, and Zr. Table 4 shows the values of biological absorption factor in plants in the Atomic Lake and the Outer Lake.

Table 4

Average content of elements in soil and plants, biological absorption factor for the areas under research, mg/kg

Element	X in soil		X in plants		biological absorption factor	
	the Outer Lake	the Atomic Lake	the Outer Lake	the Atomic Lake	the Outer Lake	the Atomic Lake
Li	30,3	25,9	0,4	1,2	0,01	0,05
B	1,6	0,8	25,5	77,3	15,7	92,4
Al	90860	101905	435	648	0,005	0,01
P	1090	938	1165	1637	1,1	1,7
Ti	5346	6425	82	333	0,02	0,1
Cr	46,2	78,6	11,9	39,1	0,3	0,5
Mn	1575	1230	140	151	0,1	0,1
Fe	7827	91553	1931	2796	0,02	0,03
Co	7,8	37,7	0,7	2,0	0,03	0,1
Ni	29,1	38,9	8,3	23,4	0,3	0,6
Cu	75,3	94,3	7,2	7,1	0,1	0,1
Zn	129	142	306	73	2,4	0,5
Ga	15,3	18,6	0,3	0,6	0,02	0,03

Table 4

Average content of elements in soil and plants, biological absorption factor for the areas under research, mg/kg

Element	X in soil		X in plants		biological absorption factor	
	the Outer Lake	the Atomic Lake	the Outer Lake	the Atomic Lake	the Outer Lake	the Atomic Lake
As	12,0	26,6	0,8	1,1	0,1	0,04
Sr	302	357	85	148	0,3	0,4
Y	14,8	16,3	0,2	0,4	0,02	0,03
Zr	84,2	85,4	2,5	5,3	0,03	0,1
Mo	0,77	3,85	0,2	0,3	0,3	0,1
Ba	528	650	20,6	32,0	0,04	0,05
La	21,8	22,9	0,4	0,8	0,02	0,03
Ce	40,0	48,7	1,27	1,90	0,03	0,04
Pb	6,2	7,4	2,31	3,74	0,4	0,5

The results of the research showed that the biological absorption factor of elements in plants at the Atomic Lake area differs from the biological absorption factor value at the Outer Lake area. Thus, for many elements, the biological absorption factor value at the Atomic Lake area turned out to be higher than that of the Outer Lake. This may indicate that the degree of soil change in the Atomic Lake area has affected the composition of the soil and plants.

In similar studies investigating the content of trace elements in plants growing on the territory of the former Semipalatinsk nuclear test site, Pleshkova S. M. et al. [28] reported elevated concentrations of Cr (up to 23 times), Sc (approximately 5–7 times), Cu (3 times), Al (2 times), and V (2 times) compared to background levels. Plants collected from the Degelen mountain massif were particularly enriched in Sc, Cr, and Mo. The concentrations of Cr exceeded global average values by 23 times, Mo by 8 times, and Sc by 5–7 times. In plants sampled from the Experimental Field, increased contents of Cr (23 times), Sc (5–7 times), Pb (1.3–4 times), and Mo (2 times) were observed.

Among the elements for which an increased biological absorption factor was found at the Atomic Lake area, one can note B, Ni. The biological absorption factor of these elements increased by more than 5 times for B, more than 2 times for Ni. This may be due to the more accessible form of these biogenic elements for plants.

4. CONCLUSION

The study established that the concentrations of most trace elements in the soils of the Atomic Lake area are significantly higher than those in the soils of the Outer Lake, indicating pronounced anthropogenic impact. For example, the average concentration of Cr in Atomic Lake soils is 78.6 mg/kg, whereas in Outer Lake soils it is 46.2 mg/kg. Compared to the upper continental crust reference values (Clarke), levels of Al and Sr in Atomic Lake soils are elevated by 1.3 times, P by 1.5 times, Ti, Mn, and Zn by 1.8 times, Fe and Co by 2.2 times, Cu and Mo by 2.5 times, and As by 4 times. Meanwhile, elements such as Li, P, and Ti exhibit concentrations close to Clarke values, suggesting minimal technogenic influence on their content. The coefficients of variation for trace elements in Atomic Lake soils are substantially higher, reflecting heterogeneous geochemical conditions, whereas Al and Fe remain stable across both water bodies. These findings confirm long-term anthropogenic effects associated with nuclear testing and chemical pollution.

In plants growing in the Atomic Lake area, significantly higher accumulation of trace elements was observed compared to plants from Outer Lake. For instance, Cr concentration in *Artemisia hololeuca* reaches 83.3 mg/kg, which is three times higher than that in plants from Outer Lake. Fe concentration in Atomic Lake plants reaches 2585 mg/kg, 2.8 times greater than in Outer Lake plants. Al content in *Carex supina* from Atomic Lake is 580 mg/kg, 2.1 times higher than Outer Lake. Concentrations of P, Ti, Sr, Y, and Ba in Atomic Lake plants are at levels comparable to or lower than those in Outer Lake. However, Fe, Cr, Co, Ni, Zn, and As levels markedly exceed those of the reference plant species. These data confirm a significant influence of radiochemical contamination on the accumulation of trace elements by plants in the Atomic Lake zone.

The biological accumulation coefficients of trace elements in plants from the Atomic Lake are considerably higher than those from the Outer Lake, indicating an increased capacity of plants to accumulate elements under anthropogenic pressure. Elevated biological accumulation coefficients of elements such as B, Co, Ni, and Cr suggest pronounced stress in vegetation related to altered mechanisms of trace element uptake and redistribution. This reflects the impact of radiological and chemical pollution, potentially leading to bioaccumulation of toxic substances and increased ecological risks to the ecosystem.

Further research should be aimed at expanding the spatial coverage of the sample and including seasonal variability. A promising direction is to conduct genetic and physiological-biochemical studies of plants to assess the mechanisms of adaptation to chronic radiation and chemical stress. In addition, a detailed study of the migration of elements in the soil–vegetation–water system, including the bottom sediments of an Atomic Lake, would provide a more complete picture of the long-term transformation of the ecosystem.

DATA AVAILABILITY

The data used in this study were obtained by the authors through original field sampling and laboratory analyses conducted in 2023 using accredited analytical procedures.

AUTHORS' CONTRIBUTION

Conceptualization – M.T. Zhailybayeva; Resources – R.M. Tazitdinova; Formal analysis – M.T. hailybayeva, Zh. Rakhymzhan; Methodology – M.T. Zhailybayeva, G.T. Kyzdarbekova; Software – M.T. Zhailybayeva; Supervision – R.M. Tazitdinova, Zh. Rakhymzhan; Visualization – M.T. Zhailybayeva; Writing—original draft preparation – M.T. Zhailybayeva; Writing—review and editing – all authors.

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БҰРЫНҒЫ СЕМЕЙ ЯДРОЛЫҚ СЫНАҚ ПОЛИГОНЫНЫҢ АТОМ КӨЛІ АУДАНЫНДАҒЫ ТОПЫРАҚ ПЕН ӨСІДІКТЕРДІҢ БИОГЕОХИМИЯЛЫҚ ЕРЕКШЕЛІКТЕРІ

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ТҮЙІН СӨЗДЕР

Семей ядролық сынақ полигоны, Атом көлі, элементтік құрамы, радиациялық ластануы, топырақ талдауы, өсімдік жамылғысы, биологиялық сіңіру коэффициенттері, Биогеохимиялық ерекшеліктері.

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АБСТРАКТ

Бұл мақалада Семей ядролық сынақ полигоны аумағында орналасқан Атом көлінің маңындағы топырақ пен өсімдіктердің элементтік құрамын кешенді зерттеу нәтижелері ұсынылған. Зерттеудің негізгі мақсаты — ұзақ мерзімді антропогендік әсер мен радиациялық сәулеленудің салдарынан қалыптасқан биогеохимиялық ерекшеліктерді түсінуге баса назар аудара отырып, топырақтар мен жергілікті өсімдіктердегі химиялық элементтердің концентрацияларын және таралу заңдылықтарын бағалау болды. Өкілдік топырақ және өсімдік үлгілерін жинау үшін далалық зерттеулер жүргізіліп, кейін заманауи аналитикалық әдістер арқылы зертханалық талдаулар жасалды. Алынған деректер элементтердің таралу заңдылықтарын анықтау және топырақтағы элементтер концентрациясы мен олардың өсімдіктер арқылы сіңірілуі арасындағы өзара байланысты зерттеу үшін мұқият статистикалық өңдеуден өтті. Өсімдіктердегі микроэлементтер концентрациясының эталонды өсімдікпен салыстырмалы талдауы жүргізілді. Топырақтағы микроэлементтер мөлшері жер қыртысының жоғарғы қабатының Кларк көрсеткіштерімен салыстырылды. Биологиялық сіңіру коэффициенттерін есептеуге ерекше назар аударылды, бұл әртүрлі өсімдік түрлерінің элементтерді селективті жинақтау қабілетін анықтауға мүмкіндік берді. Бұл коэффициенттер өсімдіктердің созылмалы радиациялық стресс жағдайына бейімделу механизмдерін бағалауға септігін тигізді. Алынған нәтижелер ядролық ластануға байланысты экологиялық қауіп-қатерлерді бағалау үшін биогеохимиялық зерттеулердің маңыздылығын көрсетеді.

БИОГЕОХИМИЕСКИЕ ОСОБЕННОСТИ ПОЧВ И РАСТИТЕЛЬНОСТИ В РАЙОНЕ АТОМНОГО ОЗЕРА БЫВШЕГО СЕМИПАЛАТИНСКОГО ИСПЫТАТЕЛЬНОГО ЯДЕРНОГО ПОЛИГОНА

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КЛЮЧЕВЫЕ СЛОВА

Семипалатинский ядерный испытательный полигон, Атомное озеро, элементный состав, радиационное загрязнение, анализ почвы, растительность, коэффициенты биологического

АБСТРАКТ

В данной статье представлены результаты комплексного исследования элементного состава почв и растительности в районе Атомного озера, расположенного на территории Семипалатинского испытательного ядерного полигона. Основной целью исследования была оценка концентраций и закономерностей рас-

поглощения, биогеохимические особенности.

пределения химических элементов в почвах и местных видах растений с акцентом на понимание биогеохимических характеристик, сформированных в результате длительного антропогенного воздействия и радиационного облучения. Для сбора репрезентативных образцов почвы и растений были проведены полевые исследования, которые затем были проанализированы в лаборатории с использованием современных аналитических методов. Полученные данные подверглись тщательной статистической обработке для выявления закономерностей распределения элементов и изучения взаимосвязи между концентрациями элементов в почвах и их усвоением растениями. Был проведен сравнительный анализ результатов полученных концентраций микроэлементов в растениях с концентрацией микроэлементов в эталонном растении. Результаты измерений содержания микроэлементов в исследуемых почвах сравнили с показателями кларка верхней части континентальной коры. Особое внимание было уделено расчету коэффициентов биологического поглощения, которые позволили получить ценную информацию о способности различных видов растений к избирательному накоплению. Эти коэффициенты позволили оценить адаптационные механизмы, выработанные растительностью в ответ на хронический радиационный стресс. Полученные результаты подчеркивают важность биогеохимических исследований для оценки экологических рисков, связанных с ядерным загрязнением.

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