Egypt. J. Soil Sci. **Vol. 65**, No. 2, pp: 1231 - 1200 (2025)

Egyptian Journal of Soil Science

http://ejss.journals.ekb.eg/

Accumulation, Distribution, and Transformation of Heavy Metals in the Dried Bottom Soils of the Aral Sea

Zafarjon Jabbarov [1]*, **Tokhtasin Abdrakhmanov** [1], **Shokhrukh Abdullaev** [1], **Samad Makhammadiev** [1], **Urol Nomozov** [2], **Otamurod Imomov** [1] and **Dilafruz Makhkamova** [1]

[1]*National University of Uzbekistan, Tashkent, 100174, Uzbekistan*
[2]*Tashkent branch of the Samarkand state university veterinary medicine of livestock and biotechnologies, Chilanzar, 35a, Uzbekistan*

THE ARTICLE examines the quantity, accumulation, and distribution of elements in the soil and sediments formed on the dried-up bottom of the Aral Sea, which began drying up in 1960. It was determined that not all soils in the eastern part of the dried-up seabed are equally contaminated with heavy metals. However, the scientific analysis confirms the localized accumulation of certain heavy metals at specific points, while their distribution patterns have also been identified. The study area was divided into three zones: Zone I- the coastal areas of the Aral Sea that have been dry for 50 years. Zone II - soils formed due to wind-driven sand accumulation, which have been dry for 30 years. Zone III - located in the northern region, characterized by high salt content and dry for 25 years. The results show that in 2 zone, the Clarke concentration (Cc) of all elements is below 1. However, the heavy metals V, Co, Mn, Mo, Cd, Cu, and Zn in 1 zone and 3 have a Cc value above 1, indicating higher accumulation in these areas. The Clarke scattering (Cs), however, follows a different pattern. Heavy metals are more widely distributed in Zones II and III, particularly Ni, Mn, Co, Cu, Cr, and Zn. In the initially dried-up areas, the scattering coefficient, or Clarke concentration, remains below 1. The sequential ranking of elements by Clarke concentration in the eastern part of the dried-up Aral Sea bottom is as follows: Cd (56.46%) - Cu (15.8%) - Mo (9.9%) - Zn (9.82%) - Mn (2.3%) - Co (1.81%) - V (1.21%) - Cr (0.8%) - Ni (0.69%). This indicates that these elements have a high accumulation in the soil. In terms of scattering, the elements are ranked as follows: Co (6.5%) - Mn (5.43%) - Cu (4.02%) - V (3.27%) - Zn (3.03%) - Ni (2.07%) - Cr (1.76%) - Cd (1.15%) - Mo (0.24%). The quantity of highly dispersed heavy metals is not significantly high, and their values remain close to the Clarke concentration.

Keywords: Aral Sea, Clarke, Geochemical accumulation, Heavy metals distribution.

1. Introduction

The Aral Sea is located at the border of Uzbekistan and Kazakhstan in Central Asia. It is the fourth largest lake in the world, covering an area of 66,000 km², with a volume of 1,070 km³ and a maximum depth of 66 meters. Over the past 10,000 years, it has repeatedly dried up and refilled due to natural and anthropogenic factors (Micklin et al., 2007; Issanova et al., 2023; Su et al., 2021). Its most recent drying began in 1960 (Izhitskiy et al., 2016; Micklin et al., 2010; Ivanov et al., 1996; Wang et al., 2021), and currently only 10% of its original water remains (Aslanov et al., 2024; William, 2021). The accumulation of salts over the years has had a strong impact on plant distribution (Issayeva et al., 2021; Cui, M. Et al., 2023; Ellena, 2024). As a consequence of the Aral Sea's drying, the area has now been replaced by the Aral sands, which have different degrees of salinity. (Jabbarov et al., 2024). The decline in the groundwater level has led to an increase in salt content (Adilov et al., 2021), and the salinity of the water has reached 126–244% (Andrulionis et al., 2025; Roget et al., 2009). The salt content differs in sandy and clay soils. In particular, in the soils of the southeastern part of the Aral Sea, compounds like evgsterite ($2Na_2SO_4 \bullet CaSO_4 \bullet 2H_2O$), astraxanit ($Na_2SO_4 \bullet MgSO_4 \bullet 4H_2O$), and mirabilite ($Na_2SO_4 \bullet 10H_2O$) have formed (Kharitonova et al., 2022). It has been determined that the quantity of the following substances in the dried bottom of the Aral Sea varies: ammonium nitrate 171 mg/100 g; $(NH_4)3PO_4$ 206 mg/100g; K_2SO_4 140 mg/100g; $CoSO_4$ 5.5 mg/100g; H_3BO_3 39 mg/100g; $ZnSO_4$ 7.8 mg/100g; $FeSO_4$ 242 mg/100g; $CuSO_4$ 15.6 mg/100g; $MnSO_4$ 163 mg/100g; $CaSO_4$ 2700 mg/100g, and of course, this quantity varies across different regions (Kushiev et al., 2023; Andrulionis et al., 2021; M.M. Ulbekova et al., 2024). The variation in elements in the dried bottom soils of the Aral Sea is inherited from aeolian, clay, and alluvial deposits (Pokrovsky et al., 2017).

*Corresponding author e-mail: zafarjonjabbarov@gmail.com
Received: 18/03/2025; Accepted: 11/06/2025
DOI: 10.21608/ejss.2025.369277.2070

Pollution has resulted from the influx of urban and industrial wastewater over the years, as well as drainage water (Gadalia et al., 2008; Klimaszyk et al., 2022; Kholdorov et al., 2023). Specifically, pollution has occurred due to industrial activities involving Pb and Cd, and due to the use of pesticides and fertilizers in agriculture, which have led to contamination with elements such as NO_3, Zn, Ni, Hg, and Mn (Zhan et al., 2022; Issanova et al., 2022). The Aral Sea is nourished by the Amu Darya and Syr Darya rivers, and over the years, pollution and accumulation of various elements have been observed (Jana Friedrich, 2009; Zhang et al., 2021). This is especially noticeable in the lower flows of the rivers (Peifang Leng et al., 2021; Crosa et al., 2006; Lars Gerlitz et al., 2020; Mayar et al., 2024). The composition of the Syr Darya water flowing into the Aral Sea from its source in Kyrgyzstan has been studied, and the results show that the concentration of elements is below international standards, but the levels of heavy metals such as Cu, Pb, Zn, and Cd in the Aral Sea water have increased, which could be related to human activities (Ma et al., 2019). The soils at the bottom of the Aral Sea are salinized to varying degrees, enriched with sodium, magnesium, and calcium, and contaminated with heavy metals like Cd and Zn (Issanova et al., 2023). They may be mainly contaminated due to the use of chemical fertilizers in agriculture (Nasrulin et al., 2001; Abdrakhmanov, et al., 2023). These soils have a high concentration of soluble salts such as chlorides, sulfates, sodium, and bicarbonates. According to the results of soil salinization, at a depth of 1 meter, sulfate-chlorides dominate: sulfate-chloride (57%), chloride-sulfate (28%), and soda-sulfate (14%). The cation and anion composition of the studied soil can be ranked as follows: $Cl > SO_4 > HCO_3 > Ca > Na+K > Mg$. Based on the level of salinization, highly (strongly) salinized soils and saline soils dominate the dry bed of the Aral Sea (Issanova et al., 2022; Jabborova et al., 2023; Jabbarov et al., 2024).

In the dried bed of the Aral Sea, unique trace elements are distributed differently, depending on their geological location (Li, Y. et al., 2024; Ershova et al., 2024). The distribution and accumulation of heavy metals such as Cd, Co, Cu, Ni, Zn, and the element Mn in the waters of the Syr Darya river flowing into the Aral Sea and in the soils of the related regions have been studied, and it has been determined that their concentrations exceed the standard levels (Ma et al., 2019; Xiangtong Huang et al., 2011; Bagdat Satybaldiyev et al., 2023). In the soils of the dried bed of the Aral Sea, the levels of exchangeable cations Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+} have changed due to plant cultivation (Jiae An et al., 2020). In the dried bed of the Aral Sea in Kazakhstan, the distribution of elements, including the heavy metals in the water flowing from the Syr Darya, has been studied. It was found that the concentrations of elements such as Al, As, B, Ba, Cd, Cr, Cu, Ni, Pb, Sb, Ce, Eu, Er, Gd, La, Nd, Pr, Sc, Sm, Dy, Ho, Lu, Tb, Tm, Y, and Yb were examined. Among these, Al (average 851 µg/L), As (35.8 µg/L), Cd (2.8 µg/L), and Pb (10.1 µg/L) were found to be above the standard limits (Rzymski et al., 2019). The concentration of magnesium in irrigation water has increased, which is considered hazardous (Bagdat aldiyev et al., 2023). In the northern regions of the dried Aral Sea, soil contamination has been observed since 1970, with the accumulation of elements such as V, Cr, Zn, Co, Pb, Ni, Cu, and Cd (Liu et al., 2020).

Over the years, organic carbon has accumulated and increased in the sediments of the Aral Sea, due to plant residues (Feng et al., 2021). Based on the analysis of the above literature, it can be concluded that the drying of the Aral Sea and the formation of sand dunes in its place, along with the accumulation and distribution of elements during soil formation over time, have been observed, and in certain areas, contamination with heavy metals has been identified.

2. Materials and Methods

2.1. Study area

The research area is located on the borders of Uzbekistan and Kazakhstan in Central Asia, where salinized soils of varying degrees are spread across the dried bed of the Aral Sea (Figure 1).

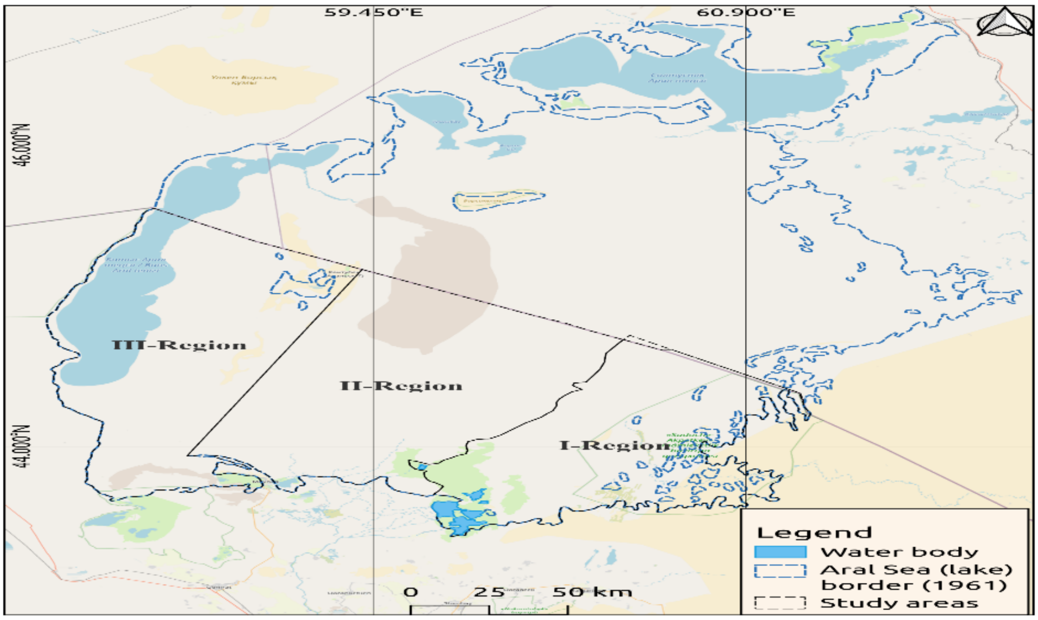

Fig. 1. Study area former Aral Sea (lake). Source: www.osm.com adapted by QGIS.

The research was conducted on the soil-ground layers formed in the eastern part of the dried bed of the Aral Sea, where soil samples were taken from 25 sampling points along the south-to-north direction in the eastern region, with profiles excavated and samples collected (Table 1).

Table 1. Research area and location of soil samples.

Profile	***Coordinates***	***By WRB classification***	***Research region.***
P1	43°41′81.57″N 60°18′10.42″E	Arenasols	
P2	43°43′74.09″N 60°17′93.05″E	Arenasols	
P3	43°47′05.46″N 60°15′90.07″E	Arenasols	
P4	43°59′31.49″N 60°16′61.37″E	Arenasols	
P5	43.67′43.37″ N 60.17′17.23″E	Arenasols	
P6	43.67′43.37″N 60.17′17.23″E	Arenasols	
P7	43.78′71.65″N 60.19′12.02″E	Arenasols	*I- region*
P8	43.82′89.45″N 60.19′95.43″E	Arenasols	
P9	43°86′09.66″N 60°22′54.35″E	Arenasols	
P10	43°93′26.33″N 60°25′45.61″E	Arenasols	
P11	43°95'70.27"N 60°28'11.69"E	Arenasols	
P12	43°95'73.42"N 60°28'07.56"E	Arenasols	
P13	43°95'52.54"N 60°28'29.81"E	Arenasols	
P14	43°95'50.79"N 60°28'38.87"E	Arenasols	
P15	43°99'97.3"N 60°11'24.33"E	Arenasols	
P16	44°03'97.49"N 60°34'80.65"E	Arenasols	
P17	44°04'01.75"N 60°34'74.79"E	Arenasols	*II- region*
P18	44°04'11.65"N 60°34'65.11"E	Arenasols	
P19	44°04'22.33"N 60°34'48.918"E	Arenasols	
P20	44°04'16.57"N 60°34'61.7"E	Solonchaks	
P21	44°06'40.60"N 60°37'16.72"E	Solonchaks	
P22	44°11'40.62"N 60°17'16.57"E	Solonchaks	*III- region*
P23	44°15'27.41"N 60°12'19.38"E	Solonchaks	
P24	44°20'39.33"N 60°16'14.24"E	Solonchaks	
P25	44°28'25.09"N 60°26'18.16"E	Solonchaks	

The soil formation in the areas where the soil samples were taken is not uniform. The region between points P1 and P13 is the first area of the Aral Sea to dry up, and it has been dry for 50 years. The region between points P14 and P19 consists of soils formed by windblown sand accumulation and has been dry for 30 years. The region between points P20 and P25 is located in the northern part, where saline soils with high salt content have formed, and it has been dry for 25 years.

2.2. Geology and Parent Material of Soil Formation

The Aral Sea basin was formed 2.2–2.0 million years ago as a result of the combined effects of exogenous and endogenous processes of landform development. The main influence in these processes was the active development of exogenous processes associated with tectonic movements (Kess, 1991). According to scientists, if the deepening due to deflation was on average 150 meters, then during the formation of the basin, 15,000 km^3 of material could have been lost. Before 1957, the volume of water in the Aral Sea was 1,075 km^3. If the deepening rate was 4 cm per year, the basin would have deepened over 3,750 years, or approximately four thousand years, which corresponds to data presented in scientific literature (Kess, 1969; Maev, 1983; Rubanov, 1987). At that time, alluvial-lake grayish-brown clays and light yellowish-brown feldspathic quartz sands were deposited along the Aral. This period can be linked to the formation of an abrasive terrace on the eastern slope of Ustyurt, which was identified by Y.M. Kleiner and V.I. Kravchuk at absolute heights of 70 + 73 meters (Kleiner, 1966). According to A.S. Kess, the development of the Aral during the early and middle Pleistocene occurred in subaerial conditions. The early accumulative eopleistocene surface underwent significant changes due to eolian processes, which led to the formation of deeply incised deposits and vegetation landforms. The central part and the ridge were deepened by several meters due to deflation (Kess, 1991).

2.3. Geomorphology

In the study of relief, according to A.K. Kurbaniyazov, its age, genesis, and morphology should be considered. The dried relief of the shores and seabed of the Aral Sea is associated with the ancient and recent Aral transgressions. The dried seabed of the Aral is partially divided in the direction of the water, with sandy dunes covered with salt, at a depth of 0–1 meters, which constitute the initial accumulative marine ridges (Kurbaniyazov, 2017). According to Kess, the relief formed as a result of the ancient Aral transgression appeared approximately 3,000 years ago, and its distribution was very limited (Kess, 1991).

2.4. Soils

Soil formation in the dried bed of the Aral Sea continues. According to the soil formation theory, soil may not exist yet because soil forms at a rate of 1 cm per 200 years. The drying of the Aral Sea began in 1960, and 65 years have passed, so the formation of soils can now be observed. However, the drying of the Aral Sea has occurred repeatedly: the initial drying phase occurred in the 15th century BC, the second phase was observed in 1211 AD, and the third phase began in 1960 (Dukhovny, 2017). This indicates that, as a result of the repeated drying and refilling of the Aral Sea over several millennia, soils have formed in its place, and some soils may have appeared. It should be noted that scientists who have conducted research on the dried bed of the Aral Sea emphasize that soils have formed in the dried bed, which can be seen from the data in the following table (Table 2).

Table 2. Formation of Soil-Substrate Layers in the Dried Bed of the Aral Sea.

Location of the Area	Soil-Substrate Layer Name	Dominant Factors	References
East	Saltflat, sandy-covered saltflat, dried marshy-silty salt marsh, coastal salt marshes, salinas.	Desiccation, climate change, aridization	Tomina (2009)
Southeast	Saltflat, sandy, saline soils	Desiccation, climate change, desertification	Tomina (2009)
Western, southwestern. Central, eastern.	Semi-hydromorphic salt marshes, hydromorphic salt marshes, semi-automorphic salt marshes, automorphic salt marshes, desert-sandy soils, sands of varying degrees of consolidation.	Under the influence of variable hydrogeological conditions and arid climate.	Stulina et al. (2024)
All areas in the dried bed of the Aral Sea	Marshy salt flats, typical salt flats in lowlands, automorphic (desert sand, saltflat) soil-substrate layers in relatively deep groundwater areas.	Desiccation, climate change	Khuziev et al., (2020)
Western	Marsh salt flats, salt flats, saltflat-like, sedimentary marshes, marshes, sandy desert, sedimentary marsh mud, sedimentary marsh salt flats, marshes, sedimentary salt flats, typical salt flats, sedimentary lakes, sandy formations.	Water retreat, desertification, degradation, intense evaporation.	Ismanov and Kattaeva (2024)
Southeastern	Saline marsh hydromorph, heavily sandy hydromorph, unstable - gritty sandy, semi-hydromorph, sandy-desert, marsh-alluvial and lake-marsh hydromorphic soils, semi-hydromorph, gritty saline, alluvial-marsh semi-hydromorph, gritty saline hydromorph, (semi-hydromorph).	The desiccation of the Aral Sea and climate change.	Idirisov (2024)
Northeastern and southern	Automorphic, semi-hydromorphic, and hydromorphic sandy-desert soils, residual sea shore saline soils, semi-automorphic and semi-hydromorphic, as well as hydromorphic saline soils.	Climate change, desertification	Egamberdiev (2023)
Northeastern	Meadow, sandy, and reddish-brown soils.	Desertification, climate change	Issanova et al. (2022)
Southern, south-central	Depositional marsh, depositional marsh salinized soils.	Expansion of agricultural activity and hydrogeological process	Abdrakhmanov et al. (2023)

The article examines the accumulation and distribution of geochemical elements in the soils of the dried-up seabed of the Aral Sea. It was found that the elements vary and do not follow any specific pattern. The distribution and accumulation of elements are diverse, with some heavy metals being prevalent, indicating contamination. Although the Clarke concentration of certain chemical elements is high, their Clarke distribution has a low index. Soil formation is an evolutionary geochemical process that occurs over several thousand years and involves multiple stages (Figure 2).

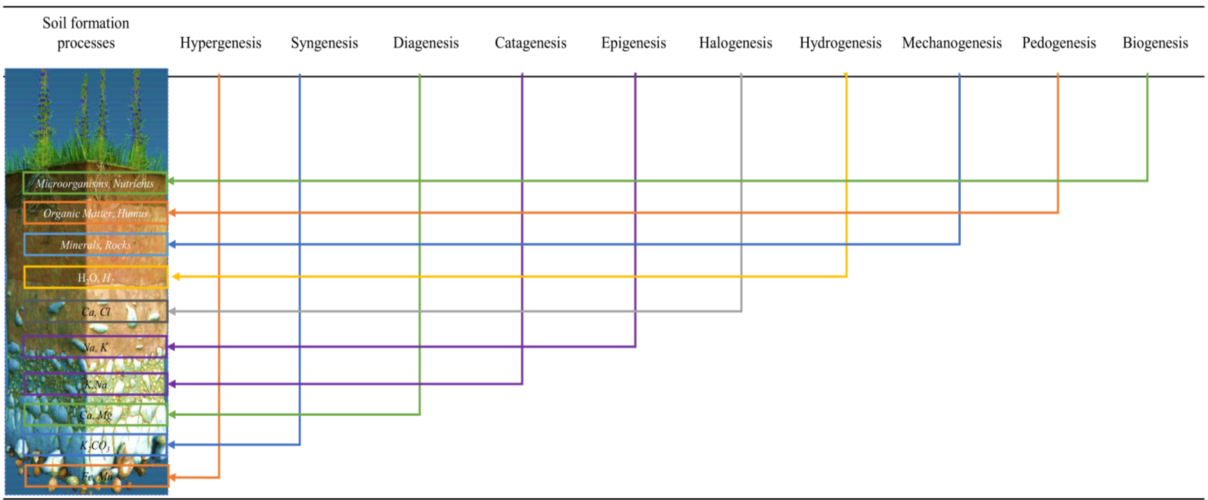

Fig. 2. The diagrammatic arrangement of the cyclosizer device.

During the formation of soils, parent rocks undergo various changes, including hypergenesis (as a result of chemical and physical changes in minerals and rocks in the upper part of the earth's crust and on its surface, Fe and Mn elements accumulate), syngenesis (as a result of excessive accumulation of sediments at the bottom of the water basin and is represented by K and Na elements), diagenesis (the initial stage of free sediments and their transition to sedimentary rocks is associated with K_2CO_3 salts), catagenesis (as a result of the petrographic and geochemical interaction of various sedimentary rocks outside the zone of diagenesis and metamorphism, chemical and mineralogical changes in rocks and are mainly associated with K and Na elements), epigenesis (secondary changes in existing sedimentary rocks and are mainly associated with Na and K elements), halogenesis (accumulation of salts from natural water bodies, mainly Ca and Cl), hydrogenesis (water The processes of entry into the lithosphere and transformation of mountain rocks (H_2O, H_2), mechanogenesis (the attraction of chemical elements and minerals and rocks as a result of mechanical movement of rocks under the influence of centrifugal forces and large axial angles in the relief), pedogenesis (the formation of soil and soil horizons under the influence of physicochemical and biochemical processes and the formation of organic products humus), biogenesis (the formation of living matter, the concentration of many chemical elements in them and the proliferation of microorganisms and nutrients) occur.

2.5. Soils

The results of the study were presented as mean and standard deviation. The distribution of heavy metals in the profiles was statistically evaluated using analysis of variance (PCoA, PERMDISP, Correlation, Regression) statistic and Clarke concentration of heavy metals (ANOVA, Correlation, Regression, Descriptive Statistics). For additional comparisons between groups, the results of PERMDISP analysis (Permutational Analysis of Multivariate Dispersions) were used. Test for equal multivariate dispersions: p (same)-0.0001, ($P < 0.05$) level was used. Heatmap was created using the Pearson and Spearman Correlation statistical program.

3. Results

3.1. Amount of elements

The amount of heavy metals in the dried Aral Sea bottom is not uniformly distributed, according to which it was found that the most common heavy metals in region I, namely Cd, Mo, Ni, Cr, were the highest in P1 soils, and their content was also high in P5 and P9 soils. In region II, their content decreased, in particular, in P11, P12, P13, P14, P15 soils, while in region III it was slightly higher, and decreased again in P24 and P25 soils (Figure 3).

Fig. 3. The content of heavy metals in the dry bottom of the Aral Sea.

In the same regions, the amount of heavy metals was similar to the above elements, and was highest in region I, including in soils P1, P5, P9, decreased sharply in soils II, including P10, P11, P12, P13, P14, P15, and slightly increased in region III. In order to determine the level of accuracy and interdependence of the obtained laboratory results and to know the group accuracy, statistical analysis results (PCoA, PERMDISP, Correlation, Regression) were performed. In order to visualize the relationships between the profiles in the research object based on spatial distribution, PCoA (Principal Coordinate Analysis) analysis was performed (Figures 4).

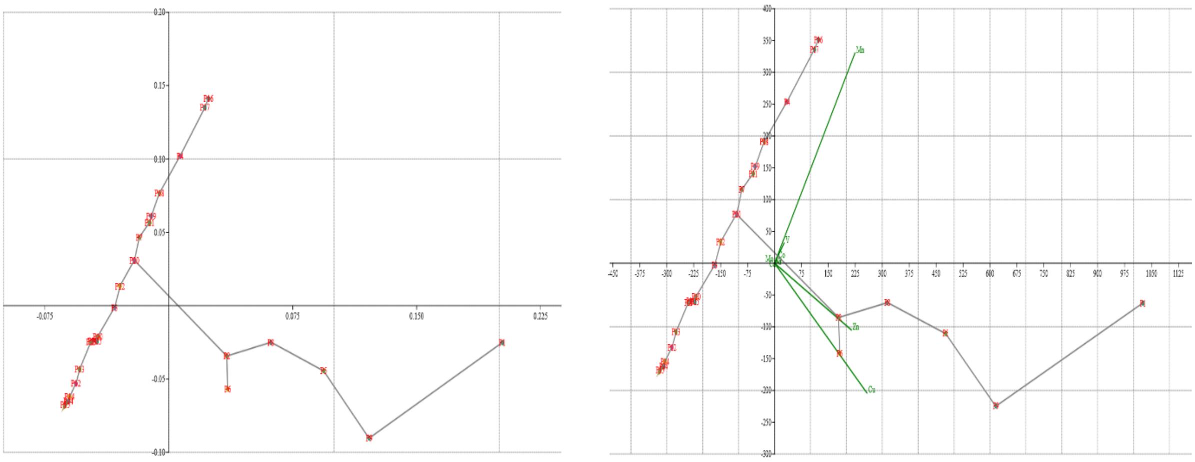

Fig. 4. PCoA analysis of profiles in the research object.

Some groups have clusters of samples, which indicates low internal variance. Such groups may have similar characteristics and may have been exposed to similar environmental or experimental conditions. Some groups have widespread samples. If samples within a group are far apart, this indicates high variance. These groups may be structurally different or may be responding differently to the environment. The results of Principal Coordinate Analysis may reflect not only the group centers, but also the differences in distribution within the group. In order to determine this and to know exactly which groups differ, PERMDISP (Multivariate Dispersion Analysis) analysis was also performed. According to it, some groups, such as P2, P10, P15, have much larger variance than other groups. This indicates that individual differences within the groups are higher, more widespread, and heterogeneity (variability) is higher. Other groups (e.g., P4, P6, P8) have relatively low variance and lower levels of internal variability (Figures 5).

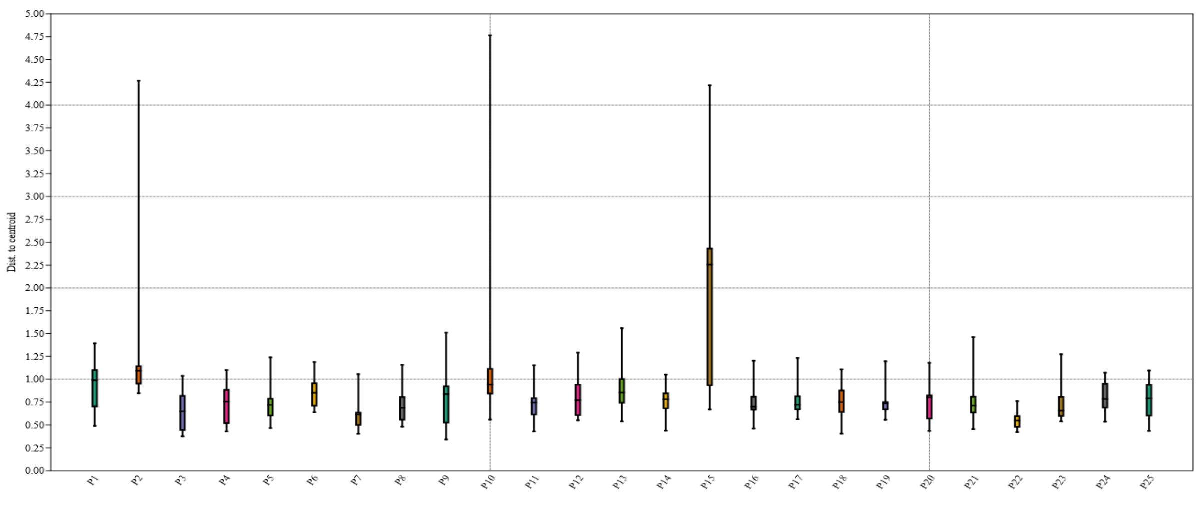

Fig. 5. Results of PERMDISP analysis, Test for equal multivariate dispersions: F-4.798, p (same)-0.0001, ($P < 0.05$).

The graph in Fig.5. confirms the PERMDISP results and shows that the variance within groups is significantly different. This means that it is important to take into account the effect of PERMDISP variance when interpreting the Principal Coordinate Analysis results. The relationship between the heavy metals detected in the study area was visually analyzed using a correlation matrix. The pairs with high correlations in yellow and orange (r ≈ 0.7 - 1.0), V and Cr, Ni and Co, Mn and Ca elements are strongly related and may affect each other (Figures 6).

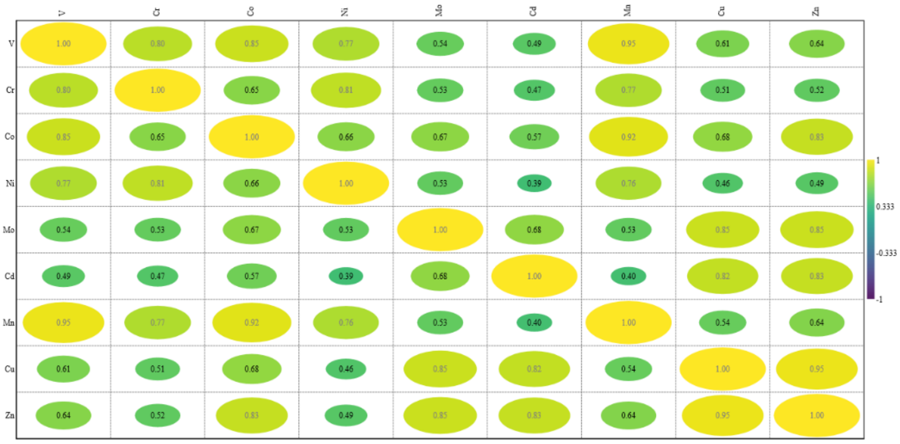

Fig. 6. Correlation matrix relationships between heavy metals.

The green pairs with medium correlation (r ≈ 0.4 - 0.7), Zn and Cr, Ca and Mn elements are correlated, but their influence is not very strong. This means that these factors partially affect each other, but their influence is not direct or other factors may also interfere. Some green and dark green ellipses and points showing an unclear relationship are considered pairs with low or weak correlations (r < 0.4).

3.2. Clarke concentration of elements

The Clarke concentration of heavy metals was calculated in soils distributed on the dry bottom of the Aral Sea, and according to the results, only the heavy metals Co, V, and Mn had a higher index than Clarke. These elements exceeded Clarke concentration in soils at points P1, P9, P16, and P17, and were lower than Clarke concentration in soils at points P2, P3, P4, P5, P6, P7, P8, P10, P11, P12, P13, P14, P15, P18, P19, P20, P21, P22, P23, P24, and P25. The results showed that the amount of heavy metals was highest in region I, lowest in region II, and relatively high in region III (Figures 7).

Fig. 7. Clarke concentration indicators of heavy metals.

It can be seen that the Clarke concentration of heavy metals Cd, Cu, Mo, Zn varies by region, in particular, in soils P1, P2, P5, P6, P8, P9 in region I, the Clarke concentration is greater than 1, while in soils P3, P4, only the amount of heavy metals Mo and Cd exceeds the Clarke, and the Clarke concentration of the remaining elements is less than 1. In regions II and III, the Clarke concentration of the heavy metal Mo is greater than 1, and that of the Cd element is close to the Clarke indicator only in P16, P17, P18, P19, P20. The changes in Clarke concentrations of heavy metals detected in the study area were determined using statistical (ANOVA, Correlation, Regression, Descriptive Statistics) analyses. The results of the Clarke indices of heavy metals in the study area showed a significantly lower negative p-value on the log scale. This means: the p-value is very small, that is, there is a significant difference between the profiles. This indicates that the results of the analysis are significant and there is no error. Very small p-values (e.g., 1.53e-156) are difficult to see on a simple scale. Therefore, a logarithmic scale was used. The results of the ANOVA analysis of the Clarke indices of heavy metals in the study area showed that there are significant differences between the profiles for each metal. This indicates that the results are good and correct (Figures 8).

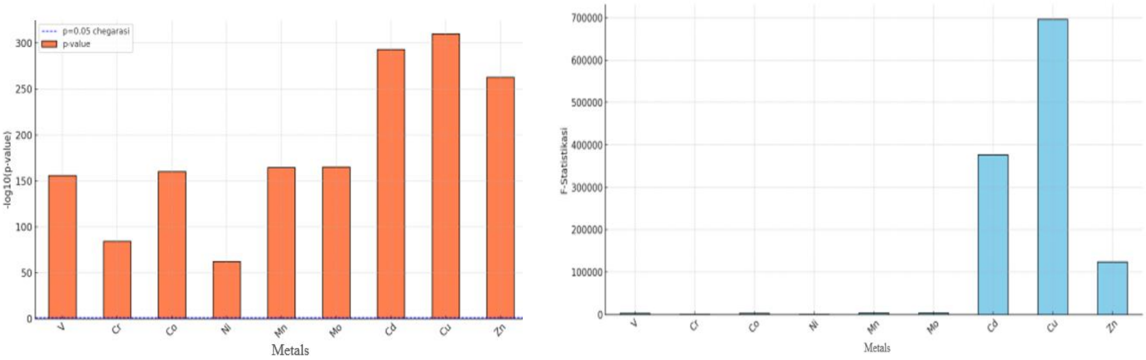

Fig. 8. ANOVA p-value and F-statistic analysis of heavy metal Ck.

According to the results of the research, it was found that the Clarke indices are very high for each metal in the F-statistics, for example: for V: F = 2461.18, for Cr: F = 173.49, for Co: F = 2908.14, for Mn: F = 3398.78 Fig.-. This means that there are large significant differences in the Clarke indices of each metal between the groups (profiles). In particular, the F-statistics of Mn and Co metals are very high, indicating that the Clarke indices between the profiles for these metals are quite large. The reason why the F-statistics of Cd, Cu and Zn elements are very high is that they differ significantly between the profiles, which led to high values of the F-statistics. The high values of the F-statistics and the small p-value together confirm that the Clarke indices are statistically significant. It was found that there were significant differences in the concentrations of each metal in the Clarke indicators along the profile. A histogram of the Clarke concentration of heavy metals for the samples was created (Figures 9). Each subgraph represents the frequency scattering of an individual metal, indicating in which range the concentration is most common. The graph shows the distributions of the metals V, Cr, Co, Ni, Mn, Mo, Cd, Cu and Zn.

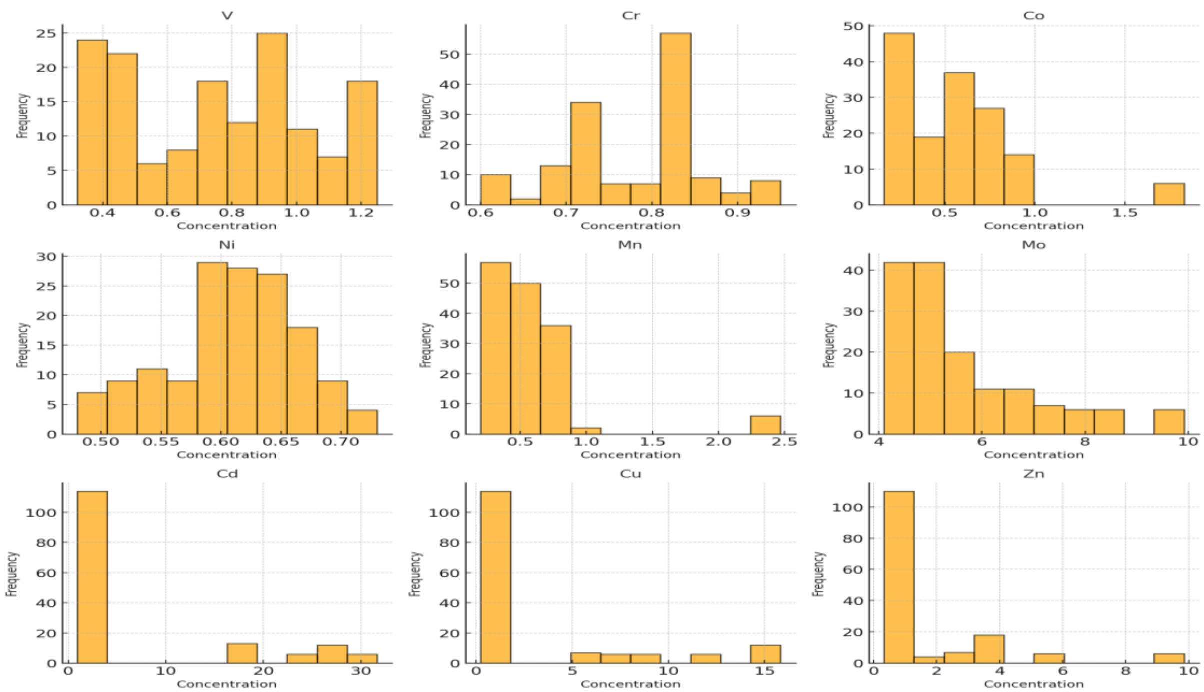

Fig. 9. Histogram of heavy metal concentration Clarke.

Histogram analysis shows that the Clarke concentrations of heavy metals vary significantly across samples. Some metals are scattering in a narrow range (e.g. Cr, Ni), while others (e.g. Cd, Mn) have a wider range.

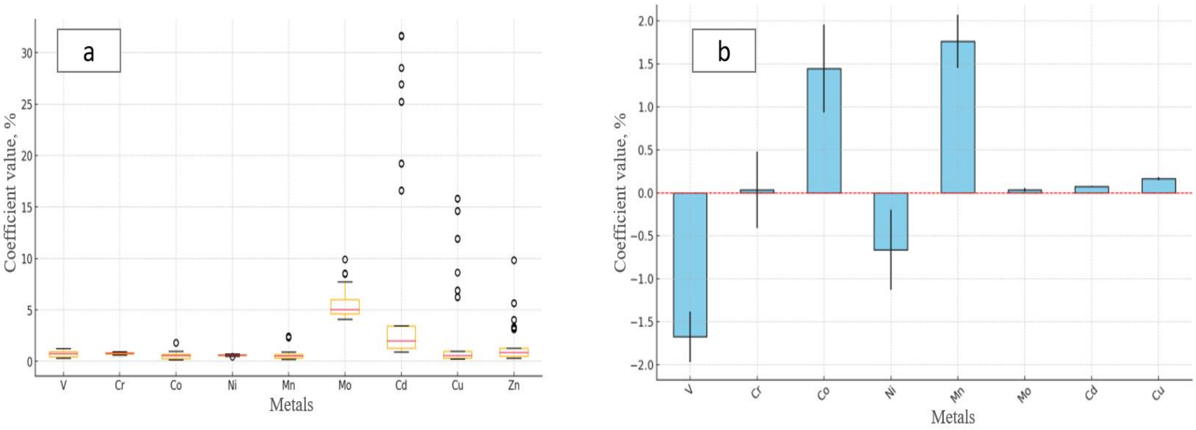

Fig. 10. Boxplot of metal concentrations and regression coefficients (a) and standard errors (b).

In both Boxplot and Bar Chart analyses, metals such as Cadmium and Molybdenum are found in high concentrations, potentially increasing environmental risk (Fig. 10a). Regression analyses of the Clarke indices of detected heavy metals show an R-squared (R^2) value of 0.993, explaining 99.3% of the variation in Zn values within these profiles through other variables. The very small value (1.53e-149) in the F-statistic and Prob(F-statistic) indicates that these profiles are statistically significant (Fig. 10b). For example, the coefficient of Mn is 1.7613, meaning that the Zn value increases by 1.76 units with a one-unit increase in Mn. Conversely, the coefficient of V is -1.6756, meaning that the Zn value decreases by 1.6756 units with a one-unit increase in V. In the p>|t| analysis, small values (less than 0.05) indicate a significant relationship. For instance, the independent variables V, Co, Mn, Cd, and Cu are significantly correlated with Zn. Monitoring highly correlated metals and identifying their common sources is crucial for environmental monitoring and management. According to the study results, the Clarke indices and Pearson correlation coefficient values indicate a linear relationship between each metal Clarke pair. A strong correlation was found between Co and Mn (0.96%), Cd and Cu (0.97%), and Cd and Zn (0.89%). Cr and Mn showed a moderate correlation of 0.48, while Cr and Zn had a weak correlation of 0.37 (Figures 11a).

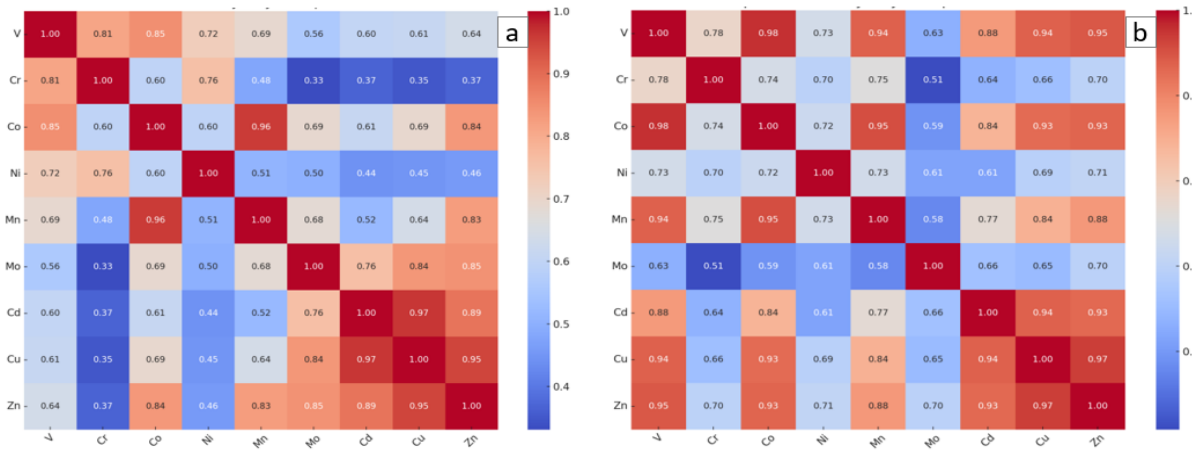

Fig. 11. Pearson (a) and Spearman (b) correlations of Clarke indices of heavy metals.

Clarke indices Spearman correlation coefficient values showed a monotonic relationship between each metal Clarke pair. According to this, it was found that Co and Zn have strong relationships of 0.93, Cd and Cu have 0.94. Cr and Mn have moderate relationships of 0.75 and Mo and Cr have weak relationships of 0.51 (Fig.-11b).

3.3. Distribution of elements

We have seen above that the Clarke concentration of heavy metals in the dry bottom of the Aral Sea is different, and the Clarke scattering index of these heavy metals is also different. The Clarke scattering index is different in the dry bottom of the Aral Sea, that is, although the Clarke scattering index of some heavy metals Cd, Cu, Mo, Zn, Co, V, Mn is high, the Clarke scattering index is less than 1.

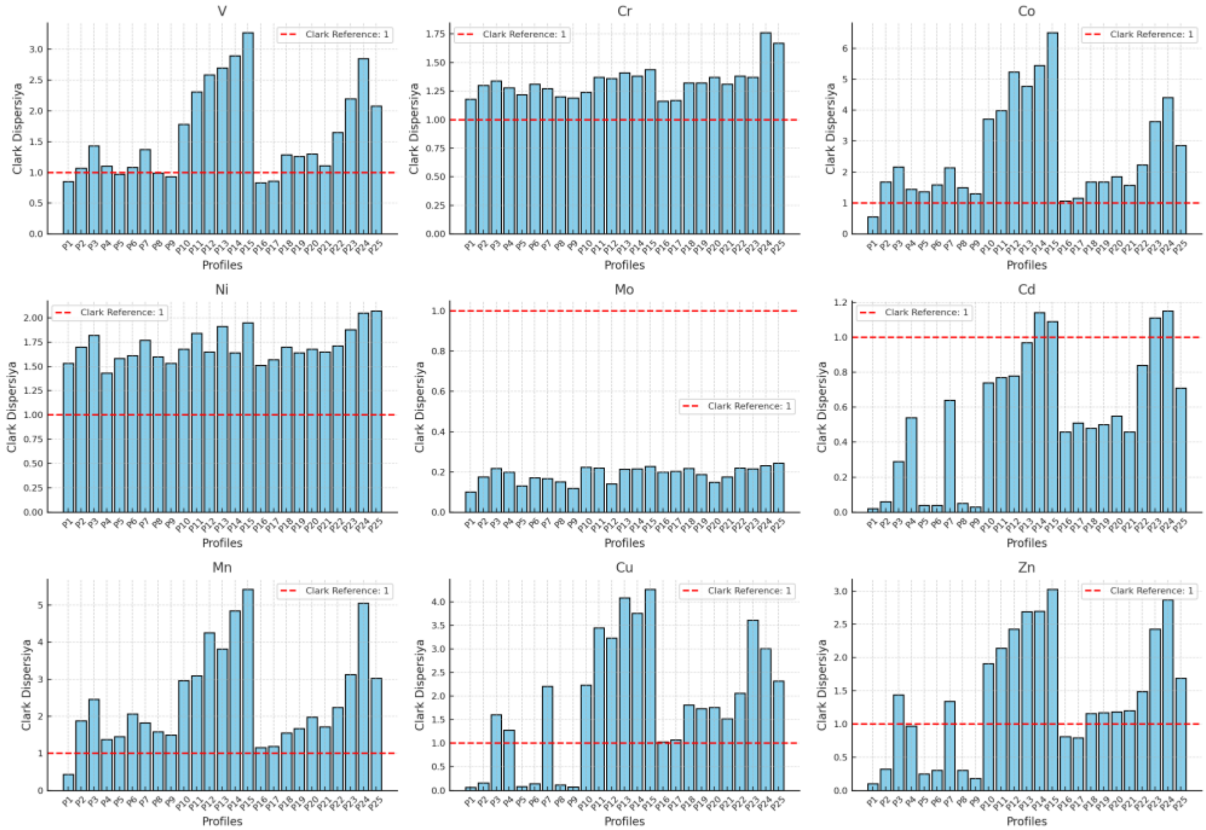

Fig. 12. Clarke scattering of Heavy Metals Across Profiles with Reference.

The distribution of heavy metals was also observed in soils of R22, R23, R24, R25 belonging to the III zone of the study area, and the lowest distribution of heavy metals was found in soils taken from points R1, R2, R3, R4, R5, R6, R7, R8, R9, R16, R17, R18, R19, R20, R21, R22. In general, the distribution of heavy metals on the dry bottom of the Aral Sea is different, and does not have a regular pattern of decreasing from south to north or increasing or decreasing according to the coordinates of location above sea level.

4. Discussion

The accumulation of heavy metals such as As, Cd, Cr, and Pb in soils formed beneath desiccated lakes has been observed (Hosseinpoor et al., 2024). In the dried bottom sediments of the Aral Sea, contamination with various organic compounds, nitrates, and heavy metals has been identified (Zhan et al., 2022; Issanova et al., 2022). According to the research findings, the soils of the studied area exhibit a high level of heavy metal accumulation. This phenomenon is primarily attributed to industrial waste contained in the waters of the Amu Darya and Syr Darya rivers, the use of mineral fertilizers in agriculture, and geochemical processes resulting from the desiccation of the Aral Sea. Over the years, heavy metals have been transported through water into the soil, leading to their increased concentration in various soil and sediment formations. The concentrations of heavy metals detected in the study area are as follows: V – 109 mg/kg (C = 90 %), Cr – 71.4 mg/kg (C = 83%), Mn – 2299 mg/kg (C = 1000%), Co– 32.6 mg/kg (C = 18%), Ni – 40.5 mg/kg (C = 58%), Mo) – 10.9 mg/kg (C = 1.1%), Cu– 741 mg/kg (C = 47%), Zn – 815 mg/kg (C = 83%). Based on Clarke concentrations, the metals can be ranked in terms of accumulation as follows: Cd (56.46%) → Cu (15.8%) → Mo (9.9%) → Zn (9.82%) → Mn (2.3%) → Co (1.81%) → V (1.21%) → Cr (0.8%) → Ni (0.69%). These results indicate that cadmium (Cd) exhibits the highest level of accumulation, while vanadium (V) is the least accumulated metal. The concentration of heavy metals varies across the studied regions, with their distribution observed in the following order:

Region I – The highest accumulation area, corresponding to the region where the Aral Sea has been desiccated for 50 years. This area has undergone active soil formation from parent rocks, and geochemical processes have led to significant heavy metal accumulation.

Region III – A moderately accumulated area, where the Aral Sea has been desiccated for 30 years, and soil formation is still ongoing.

Region II – The lowest accumulation area, characterized by the formation of sandy deposits. Due to strong wind-driven leaching of mineral substances, the heavy metal concentration remains low. The accumulation of heavy metals follows the increasing order: Region II → Region III → Region I. This trend is associated with the time elapsed since the Aral Sea's desiccation and the intensity of soil formation processes. Geochemical analysis indicates that the spatial distribution of heavy metals in the soil varies. Their decreasing order of scattering is as follows: Co (6.5%) → Mn (5.43%) → Cu (4.02%) → V (3.27%) → Zn (3.03%) → Ni (2.07%) → Cr (1.76%) → Cd (1.15%) → Mo (0.24%). Based on these results, it can be concluded that the most widely dispersed heavy metals are Co, Mn, Cu, V, Zn, and Ni, while Mo (molybdenum) is the least dispersed. Although these metals are widely distributed, their Clarke concentrations remain low, indicating that small amounts of heavy metals are spread over large areas. In summary, the desiccation of the Aral Sea has been one of the primary factors contributing to the accumulation of heavy metals in the soil. The highest accumulation was observed in Region I, while the lowest accumulation was recorded in Region II. Based on Clarke concentration values, cadmium (Cd) exhibited the highest accumulation, whereas vanadium (V) showed the lowest. The distribution of heavy metals is influenced by wind and water erosion processes, leading to their scattering over a large area in limited concentrations.

The research findings are crucial for assessing the environmental condition of the region and determining the level of heavy metal contamination. These analytical results serve as a foundation for future studies, providing essential data for soil environmental monitoring and the implementation of land reclamation efforts.

5. Conclusions

If we consider the last drying period of the Aral Sea starting from 1960, 65 years have passed to date. During this period, a gradual decrease in water levels and the formation of sandy areas have been observed. The emergence of soil on the dried seabed has also been noted, leading to the formation of soil-ground structures. Taking into account that the Aral Sea had also dried up several thousand years ago, soil formation has occurred in these regions over tens of thousands of years. When the sea refilled, previously formed soils remained submerged. During this evolutionary process, the emergence of elements, particularly the accumulation of heavy metals, has been observed. The presence, accumulation, and distribution of heavy metals such as V, Co, Mn, Mo, Cd, Cu, and Zn in this region can be attributed to two main reasons. The first reason is that these heavy metals are naturally found within soil-forming parent rocks (minerals). The second reason is the long-term discharge of wastewater and industrial effluents into the Syr Darya and Amu Darya rivers, along with the application of mineral fertilizers, which led to the transport and sedimentation of these heavy metals in the Aral Sea. It has been determined that the entire eastern part of the dried seabed of the Aral Sea is not uniformly contaminated with heavy metals; rather, scientific evidence suggests that accumulation has occurred only at certain points. The distribution of some heavy metals has also been identified. According to the results, the Ck of all elements in Zone II is less than 1. However, in Zones I and III, the Clarke concentration of heavy metals such as V, Co, Mn, Mo, Cd, Cu, and Zn exceeds 1, indicating high accumulation in these areas. The Cs, however, shows a different trend, with a higher distribution of heavy metals in Zones II and III. Specifically, the distribution of Ni, Mn, Co, Cu, Cr, and Zn has been identified. In the initially dried areas, the distribution index of heavy metals and the Clarke concentration are both less than 1. When ranking the elements in the eastern part of the dried seabed of the Aral Sea based on Clarke concentration, the following sequence is observed: - Cd (56.46%) - Cu (15.8%) - Mo (9.9%) - Zn (9.82%) - Mn (2.3%) - Co (1.81%) - V (1.21%) - Cr (0.8%) - Ni (0.69%). This indicates a high accumulation of these elements in the soil. Regarding distribution, the results are as follows, - Co (6.5%) - Mn (5.43%) - Cu (4.02%) - V (3.27%) - Zn (3.03%) - Ni (2.07%) - Cr (1.76%) - Cd (1.15%) - Mo (0.24%). Although the highly distributed heavy metals do not exist in large quantities, their levels are close to the Clarke index. In the initially dried areas, particularly in Zone I, where vegetation growth and soil cover are well developed, the distribution of heavy metals is low. Therefore, when assessing heavy metal contamination in the soils of the dried seabed of the Aral Sea, it is more appropriate to consider the Clarke concentration rather than the Clarke scattering. According to the Clarke index, the distribution of heavy metals is high in region II, in particular, the highest results were found in soils P10, P11, P12, P13, P14, P15, and heavy metals are widely distributed in these regions. From the above results, it can be seen that the Clarke concentration of heavy metals varies by element, which determines the level of accumulation of heavy metals in the regions.

List of abbreviations:

Permutational analysis of multivariate dispersions (PERMDISP)
Principal coordinate analysis (PCoA)
Clarke (C)
Clarke scattering (Cs)
Clarke concentration (Cc)
Analysis of variance (ANOVA)

Declarations

Ethics approval and consent to participate

Consent for publication: The article does not contain any material that is unlawful, defamatory, or would in any way violate the terms and conditions set forth in the contract if published.

Availability of data and material: Not applicable.

Competing interests: The authors declare that there is no conflict of interest in the publication.

Funding Statement: This article was carried out as part of the project financed by the Innovation Development Agency of the Republic of Uzbekistan under the project number FL-8323102111-R1, titled “Creating a scientific basis for grouping areas for planting plants according to the salinity, physical, chemical, and biological properties of the soils distributed in the dry bottom of the Aral Sea.

Authors' contributions: Authors YB, AH, FE wrote the original draft and YB, AH, AE, MS, MS, A.O. edit and finalize the manuscript. All authors read and agree for submission of the manuscript to the journal.

Acknowledgments: The authors express their gratitude to the Agency for Innovative Development of the Republic of Uzbekistan and the leadership of the Faculty of Biology, who funded this research under the FL-8323102111-R1 project.

References

Andrulionis, N, Zavialov O & Izhitskiy S. (2021). Current Evolution of the Salt Composition of Waters in the Western Basin of the South Aral Sea. Oceanology, 61(6), 899–908

Andrulionis N, Izhitskiy S, Savvichev S & Zavialov O. (2025). Recent changes in physical and biogeochemical state in residual basins of the Aral Sea. Aquatic Geochemistry, 31(1), 1.

Aslanov I, Teshaev N, Jabbarov Z, Opp C, Oymatov R, Karimov Y & Henebry G. (2024). Characterizing land surface dynamics in Aral Sea basin of Uzbekistan using climatic and remote sensing data to project future conditions. E3S Web of Conferences, 575, 04009.

Bekzod A, Habibullo S, Fan L, Li K, Ma X & Li Y. (2021). Transformation of vegetative cover on the Ustyurt Plateau of Central Asia as a consequence of the Aral Sea shrinkage. Journal of Arid Land, 13(1), 71–87.

Boomer I, Aladin N, Plotnikov I & Whatley R. (2000). The palaeolimnology of the Aral Sea: A review. Quaternary Science Reviews, 19(13), 1259–1278.

Crosa G, Froebrich J, Nikolayenko V, Stefani F, Galli P & Calamari D. (2006). Spatial and seasonal variations in the water quality of the Amu Darya River (Central Asia). Water Research, 40(11), 2237–2245.

Cui M, Zheng X, Li Y & Wang Y. (2023). Analysis of NDVI Trends and Driving Factors in the Buffer Zone of the Aral Sea. Water, 15(13), 2473.

Egamberdiev J. (2023). Properties and Characteristics of the Aral Region Soils, Formation of Soils on the Dried Bottom of the Aral Sea. PhD Dissertation in Biological Sciences. Fergana State University,. 135 p.

Ershova V, Prokopiev A & Stockli D. (2024). Provenance of Detrital Rutiles from the Triassic–Jurassic Sandstones in Franz Josef Land (Barents Sea Region, Russian High Arctic): U-Pb Ages and Trace Element Geochemistry. Geosciences, 14(2), 41.

Feng S, Ma L, Abuduwaili J, Liu W, Saparov G, & Issanova G. (2021). Organic Carbon Burial in the Aral Sea of Central Asia. Applied Sciences, 11(15), 7135.

Gadalia A, Motelica-Heino M. (2008) Role of the sediments in scavenging inorganic contaminants in the Syr Daria River and the Small Aral Sea (Kazakhstan). International Symposium on Sediment Management, Jul, Lille, France. pp.335-342.

Gerlitz L, Vorogushyn S & Gafurov A. (2020). Climate informed seasonal forecast of water availability in Central Asia: State-of-the-art and decision making context. Water Security, 10, 100061.

Huang X, Oberhänsli H, Suchodoletz H, & Sorrel P. (2011). Dust deposition in the Aral Sea: Implications for changes in atmospheric circulation in central Asia during the past 2000 years. Quaternary Science Reviews, 30(25–26), 3661–3674.

Ismonov A, Dosaliev A, Mamajonova O. (2022) Reclamation status of soil-ground layers on the dried bottom of the central Aral Sea // Bulletin of UzMU.. - No. 3/2/1. – P. 52-55.

Issanova G, Abuduwaili J, & Tynybayeva K. (2023). Soil Cover of the Dried Aral Seabed (Aralkum) (pp. 33–60). Cham: Springer Nature Switzerland.

Issanova G, Abuduwaili J, Tynybayeva K, Kalybayeva A, Saduakhas A, Kulymbet K, Tanirbergenov S. (2022). Soil salinisation as a land degradation process in the dried bed of the North-eastern Aral Sea, Kazakhstan. Arabian Journal of Geosciences, 15(11), 1055.

Issayeva A, Yeshibayev A, Leska B, Messyasz B, Abubakirova A. & Tleukeyeva A. (2021). Comparative Assessment of Geomorphological and Landscape Features Around the Small Aral Sea. Journal of Ecological Engineering, 22(10), 73–

84.

Ivanov Y, Chub V, Subbotina I, Tolkacheva A & Toryannikova V. (1996). Review of the scientific and environmental issues of the Aral Sea basin. In P. P. Micklin & W. D. Williams (Eds.), The Aral Sea Basin (pp. 9–21). Berlin, Heidelberg: Springer Berlin Heidelberg

Izhitskiy A. S, Zavialov P. O, Sapozhnikov P. V, Kirillin G. B, Grossart H. P, Kalinina O. Y, Kurbaniyazov A. K. (2016). Present state of the Aral Sea: Diverging physical and biological characteristics of the residual basins. Scientific Reports, 6(1), 23906.

Jabborova D, Abdrakhmanov T, Jabbarov Z, Abdullaev Sh, Azimov A, Mohamed I, Elkelish A. (2023). Biochar improves the growth and physiological traits of alfalfa, amaranth and maize grown under salt stress. PeerJ, 11, e15684.

Jabbarov Z, Abdrakhmanov T, Tashkuziev M, Abdurakhmonov N, Makhammadiev S, Fayzullaev O, Nomozov N, Kenjaev ., Abdullaev Sh., Yagmurova D, Abdushukurova Z, Iskhakova I., Kováčik P, (2024) Cultivation of plants based on new technologies in the dry soil of the Aral Sea. E3S Web Conf. Volume 497, 2024 5th International Conference on Energetics, Civil and Agricultural Engineering (ICECAE 2024) https://doi.org/10.1051/e3sconf/202449703008

Tairov, A. (2023). Information chronicle of the evolution of the Aral sea. Geography and Water Resources, (1), 12–23.

Kattayeva G. (2024) Genetic, Ecological, and Reclamation Properties of Soil-Ground Layers on the Dried Bottom of the Aral Sea (Case study of the western part). PhD Dissertation in Biological Sciences. Tashkent, TATI,. 154 p.

Kess A.S. (1969).Main Stages of Development of the Aral Sea, Problems of the Aral Sea. Moscow: Nauka,. – Pp. 41–47.

Kess A.S. (1991) Natural History of the Aral Sea and the Aral region. Izvestiya of the Academy of Sciences of the USSR. Series: Geography. No. 4. – P. 36-42.

Kharitonova G, Stulina V, Shein E, Dembovetskii V, & Krutikova, V. O. (2022). Salt Neoformations in the Soils of the Aral Sea Dried Bottom. Moscow University Soil Science Bulletin, 77(3), 142–152. doi: 10.3103/S0147687422030061

Kholdorov S, Jabbarov Z & Shamsiddinov T. (2023). Soil governance: A review of the current legislative framework for managing soil resources in Uzbekistan. Soil Security, 13, 100105.

Kleiner Yu, Kravchuk N. (1966). On the Ancient Terrace of the Aral Sea, Izvestiya of Universities. Series: Geology and Intelligence. No. 19. – P. 15–20.

Klimaszyk P, Kuczyńska-Kippen N, Szeląg-Wasielewska E, Marszelewski W, Borowiak D, Niedzielski P, Rzymski P. (2022). Spatial heterogeneity of chemistry of the Small Aral Sea and the Syr Darya River and its impact on plankton communities. Chemosphere, 307, 135788.

Kurbaniyazov A.K. (2017). Evolution of landscapes of the dried bottom of the Aral Sea: Monograph. – Moscow: Publishing House of the Academy of Natural Sciences. 148 p.

Kushiev Kh, Allaniyazova M, Burkhiev Z, Djuraev A & Nuriyeva O. (2023). Elemental composition in the soil layers of the dried bottom of the aral sea and balance their amounts on the basis of equivalent ratios. The Austrian Journal of Technical and Natural Sciences, (3–4), 40–46.

Leng P, Zhang Q, Li F, Kulmatov R, Wang G, Qiao Y, Khasanov S. (2021). Agricultural impacts drive longitudinal variations of riverine water quality of the Aral Sea basin (Amu Darya and Syr Darya Rivers), Central Asia. Environmental Pollution, 284, 117405.

Li Y, Saparov G, Zeng T, Abuduwaili J & Ma L. (2024). Geochemical behavior of rare earth elements in agricultural soils along the Syr Darya River within the Aral Sea Basin. Environmental Monitoring and Assessment, 196(5), 493. doi: 10.1007/s10661-024-12647-6

Liu W, Ma L & Abuduwaili J. (2020). Historical Change and Ecological Risk of Potentially Toxic Elements in the Lake Sediments from North Aral Sea, Central Asia. Applied Sciences, 10(16), 5623.

Ma L, Abuduwaili J, Li Y, Abdyzhapar U & Mu S. (2019). Hydrochemical Characteristics and Water Quality Assessment for the Upper Reaches of Syr Darya River in Aral Sea Basin, Central Asia. Water, 11(9).

Maev E.G. et al. (1983). Section of Bottom Sediments of the Central Part of the Aral Sea // Paleogeography of the Caspian and Aral Seas in the Cenozoic. – Moscow: Ch. II, Moscow State University. – P. 119-133.

Mayar M. A, Hamidov A, Akramkhanov A, & Helming K. (2024). Consideration of the Environment in Water-Energy-Food Nexus Research in the Aral Sea Basin. Water, 16(5), 658.

Micklin P. (2007). The Aral Sea Disaster. Annual Review of Earth and Planetary Sciences, 35(1), 47–72.

Micklin P. (2010). The past, present, and future Aral Sea. Lakes & Reservoirs: Science, Policy and Management for Sustainable Use, 15(3), 193–213.

Micklin P. P. (1988). Desiccation of the Aral Sea: A Water Management Disaster in the Soviet Union. Science, 241(4870), 1170–1176.

Nasrulin A, & Lieth H. (2001). Elaboration of Systems Hydroecological Monitoring of Aral Sea Basin. In M. Matthies, H.

Malchow, & J. Kriz (Eds.), Integrative Systems Approaches to Natural and Social Dynamics (pp. 249–261). Berlin, Heidelberg: Springer Berlin Heidelberg.

Pokrovsky B. G, Zaviyalov P. O, Bujakaite M. I, Izhitskiy A. S, Petrov O. L, Kurbaniyazov A. K, & Shimanovich V. M. (2017). Geochemistry of O, H, C, S, and Sr isotopes in the water and sediments of the Aral basin. Geochemistry International, 55(11), 1033–1045.

Rubanov I.V. et al. (1987). Geology of the Aral Sea. – Tashkent. 180 p.

Rzymski P, Klimaszyk P, Niedzielski P, Marszelewski W, Borowiak D, Nowiński K, Aladin N. (2019). Pollution with trace elements and rare-earth metals in the lower course of Syr Darya River and Small Aral Sea, Kazakhstan. Chemosphere, 234, 81–88.

Hosseinpoor S, Habibi Sh, Mohammadi A. (2024). Understanding heavy metal contamination in the vicinity of Lake Urmia, NW Iran: Environmental and health Perspectives. Heliyon, Volume 10, Issue 13, e34198 https://doi.org/10.1016/j.heliyon.2024.e34198

Satybaldiyev B, Ismailov B, Nurpeisov N, Kenges K, Snow D, Malakar A, Uralbekov B. (2023). Downstream hydrochemistry and irrigation water quality of the Syr Darya, Aral Sea Basin, South Kazakhstan. Water Supply, 23(5), 2119–2134.

Stulina G.V. (2024) Summary of the Final Expedition Results on the Dried Bottom of the Aral Sea. Tashkent,. 34 p.

Su Y, Wang D, Zhao S, Shi J, Shi Y, & Wei D. (2021). Examining long-term natural vegetation dynamics in the Aral Sea Basin applying the linear spectral mixture model. PeerJ, 9, e10747.

Tomina T.K. (2009) Soils of the Dried Bottom of the Aral Sea. Hydrometeorology and Ecology No. 1,. P. 60-75.

Ulbekova M, Tleuova T, Anarbayev A, Pazylova D, & Tileuberdi A. (2024). Mathematical Modeling of Sorptive Extraction of Lithium Chloride from Lithium-containing Brine of the Aral Sea Region. The Open Chemical Engineering Journal, 18(1), e18741231333549.

Wang J, Liu D, Ma J, Cheng Y, & Wang L. (2021). Development of a large-scale remote sensing ecological index in arid areas and its application in the Aral Sea Basin. Journal of Arid Land, 13(1), 40–55.

Zhan S, Wu J, & Jin M. (2022). Hydrochemical characteristics, trace element sources, and health risk assessment of surface waters in the Amu Darya Basin of Uzbekistan, arid Central Asia. Environmental Science and Pollution Research, 29(4), 5269–5281.

Zhang J, Li J, Bao Anming, Zhu Ch, Huang Y, Liu T. (2021) Spatio-temporal changes and driving factors of wetlands in the delta of the Syr Darya River-Aral Sea during 1962-2019(J). Advances in Water Science, 32(4): 587-596.