

Integrated geochemical and spatial analysis of trace element redistribution in salinized arid agro-landscapes: Evidence from the Turyanchay River basin (Azerbaijan)

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ABSTRACT

Arid agro-landscapes are highly vulnerable to the soil degradation caused by long-term irrigation and climatic constraints. This study investigated the spatial patterns and geochemical characteristics associated with trace element redistribution in salinized irrigated soils of the Turyanchay River basin (Azerbaijan). A geochemical dataset comprising 22 depth-specific sampling units from representative sampling sites was analyzed for trace element composition using energy-dispersive X-ray fluorescence spectrometry (EDXRF). A separate physicochemical dataset comprising 22 depth-specific sampling units was used to characterize soil salinity, major soluble ions, organic carbon, and humus conditions. Geochemical indices, including the contamination factor (CF) and geoaccumulation index (Igeo), together with statistical analysis and descriptive geochemical landscape mapping, were used to evaluate relative geochemical enrichment and spatial variability. The results indicate pronounced vertical differentiation and considerable spatial variability in trace element distribution. Nickel (Ni) exhibited the highest relative enrichment (CF = 28.23; Igeo = 4.23), followed by arsenic (As; CF = 6.88; Igeo = 2.20) and bromine (Br; CF = 5.12; Igeo = 1.77), whereas Fe, Rb, Y, and Zr had CF values below 1. Salinity analysis indicated substantial spatial and depth-related variability in soluble-ion composition, dry residue, and total soluble salts across the investigated soils. Statistical analysis identified significant relationships among major ions and salinity-related soil properties; the strongest relationship occurred between dry residue and total soluble salts ($\rho = 0.99$, $p < 0.001$); however, these correlations were interpreted as supporting physicochemical context rather than as direct evidence of salinity-driven trace element redistribution. The descriptive geochemical landscape map illustrated spatial differences in trace element associations across the study area, while the conceptual soil–water–geochemical interaction model provided a framework for interpreting the observed patterns. The findings indicated that trace element redistribution occurs within a spatially heterogeneous environment characterized by variations in soil salinity, alkalinity, and landscape conditions across the investigated irrigated agro-landscapes. The integrated methodological framework developed in this study may support soil quality assessment, environmental monitoring, and sustainable irrigation management in the arid and semi-arid regions affected by salinization.

Keywords: irrigation-induced salinization, trace elements, geochemical indices, soil–water interactions, spatial variability, arid agro-landscapes.

INTRODUCTION

Arid and semi-arid regions represent highly vulnerable soil–landscape systems where the stability of agroecosystems is strongly constrained

by climatic conditions and increasingly affected by anthropogenic pressures. In these environments, long-term agricultural development and irrigation practices fundamentally alter soil–water regimes, leading to salinization, disruption of

geochemical balance, and enhanced redistribution of chemical elements within the soil profile (Rengasamy, 2010; Qadir et al., 2014; Corwin, 2021; Food and Agriculture Organization of the United Nations, 2021).

Recent studies emphasized that the mobility, accumulation, and spatial redistribution of trace elements in soils are controlled by the complex interactions between soil properties, hydrological processes, and anthropogenic forcing (Brady and Weil, 2017; He et al., 2005; Kabata-Pendias, 2011; Tóth et al., 2016; Yang et al., 2021). In arid irrigated systems, the combined effects of high evapotranspiration, alkaline soil conditions, limited natural drainage, and continuous irrigation create strong geochemical gradients that govern trace element fractionation and redistribution (Assouline, 2021; Chu et al., 2023; Corwin, 2021; Cui et al., 2023; Mukhopadhyay et al., 2021; Wang et al., 2023; Wei et al., 2021).

Irrigation-induced salinization is recognized as one of the dominant processes shaping soil geochemistry in arid agro-landscapes. The input of mineralized irrigation water, coupled with intense evaporative concentration, promotes the formation of secondary salinity and geochemical barriers that may influence element mobility (Assouline, 2021; Corwin, 2021; Deviren Saygin et al., 2023; Ivushkin et al., 2019; Mukhopadhyay et al., 2021). Under alkaline conditions, the mobility and retention of trace elements may vary substantially depending on element speciation, redox conditions, mineral surfaces, carbonate chemistry, organic matter, and other soil properties. For example, Fe and Mn may exhibit reduced solubility under certain alkaline and oxidizing conditions, whereas the behavior of Br, As, and Cd is more variable and depends on their chemical forms and interactions with the soil matrix (Kabata-Pendias, 2011; McBride, 1994; Sposito, 2016; Sparks et al., 2023).

The previous studies conducted in the Turyanchay River basin have mainly addressed irrigation water quality, groundwater suitability for irrigation, and the general environmental characteristics of the basin (Jafarli, 2021; Aliyev et al., 2023). To the authors' knowledge, the previous studies in the Turyanchay River basin have not comprehensively examined the spatial and depth-related variability of trace elements in soils in relation to salinity and other soil chemical properties. The regional novelty of the present study lies in providing an integrated geochemical assessment of trace-element distribution across representative

soil profiles, sampling depths, soil types, and land-use conditions within this basin, whereas its methodological contribution is the combined application of geochemical indices (CF and Igeo), statistical analysis, interpretative spatial mapping, and a conceptual soil–water–geochemical framework. Similar knowledge gaps have also been highlighted for many irrigated arid regions worldwide (Tóth et al., 2016; Vereecken et al., 2016; Vogel et al., 2018; Xia et al., 2021; Yang et al., 2021). Consequently, the spatial and depth-related patterns of trace element distribution and their associations with salinity-related soil properties remain insufficiently characterized in the Turyanchay River basin. This knowledge gap provided the scientific basis for the present study.

The Turyanchay River basin, located within the Shirvan Plain of Azerbaijan, represents a typical irrigated arid agro-landscape characterized by low precipitation, high evaporation rates, alkaline soils, and long-term agricultural use. These conditions promote the development of pronounced salinity gradients and spatially differentiated geochemical environments. The occurrence of contrasting soil types, land-use conditions, salinity levels, and sampling depths across the investigated sites provides an appropriate basis for evaluating spatial and vertical variability in soil geochemical characteristics.

Understanding the mechanisms governing geochemical transformation in such systems is essential for assessing soil ecological status, predicting salinity evolution, and improving land management strategies. In particular, identifying patterns of trace element enrichment and depletion is critical for optimizing irrigation practices and reducing environmental risks in arid agricultural regions (Food and Agriculture Organization of the United Nations & United Nations Environment Programme, 2021; Mukhopadhyay et al., 2021; Tóth et al., 2016). Accordingly, the study examined whether spatial variations in soil salinity and alkalinity are associated with differences in trace element distribution within the investigated irrigated agro-landscapes. In addition, the study evaluated the combined use of geochemical indices (CF and Igeo), statistical analysis, and interpretative spatial mapping as an integrated methodological framework for characterizing spatial geochemical variability.

Although the lithological composition of the parent materials determines the natural geochemical background of the study area, prolonged

irrigation, secondary salinization, and evaporative concentration of dissolved salts may also contribute to the present-day redistribution of trace elements in cultivated soils. Under long-term irrigation, these processes may modify the natural geochemical equilibrium by altering soil salinity, alkalinity, and water movement, thereby potentially influencing trace element mobility and accumulation. Therefore, the present study evaluated the associations between soil salinity, alkalinity, and trace element distribution while considering the potential contribution of the natural lithogenic background in the Turyanchay River basin.

Specifically, the study aimed to: (i) characterize the physico-chemical and geochemical properties of soils across the investigated profiles and sampling depths; (ii) quantify the spatial and depth-related distribution of the measured elements; (iii) assess the degree of relative geochemical enrichment using indices such as CF and Igeo; (iv) identify spatial patterns of trace element enrichment and depletion relative to the adopted geochemical background values; (v) develop a descriptive geochemical landscape map reflecting the spatial differentiation of agro-landscapes under salinity stress; and (vi) develop a conceptual soil–water–geochemical interaction model for interpreting the processes potentially contributing to trace element redistribution under irrigation-induced salinization.

MATERIALS AND METHODS

Study area

The study was conducted in the Turyanchay River basin, located within the Shirvan Plain of Azerbaijan. The region is characterized by an arid climate, with mean annual precipitation of 270–278 mm, high evapotranspiration rates, and pronounced continentality (Jafarova, 2013). According to the Köppen–Geiger climate classification, the study area belongs to the BSk (cold semi-arid) climatic zone. The mean annual air temperature is approximately 14.5–15.0 °C, while annual evapotranspiration is about 912 mm, approximately 3.3 times the mean annual precipitation (Jafarova, 2013), indicating a pronounced climatic water deficit. The spatial distribution of the sampling sites was designed to encompass differences in geomorphological position, soil type, land use, salinity conditions, and irrigation conditions within the basin (Figure 1). Site selection was based on field reconnaissance, with locations chosen to cover contrasting combinations of these characteristics.

The geomorphology of the study area is dominated by alluvial–proluvial plains composed of Quaternary deposits. According to the national soil classification of Azerbaijan, the dominant soils of the study area are Grey soils, Grey-meadow soils, and Alluvial-meadow soils. Based on their

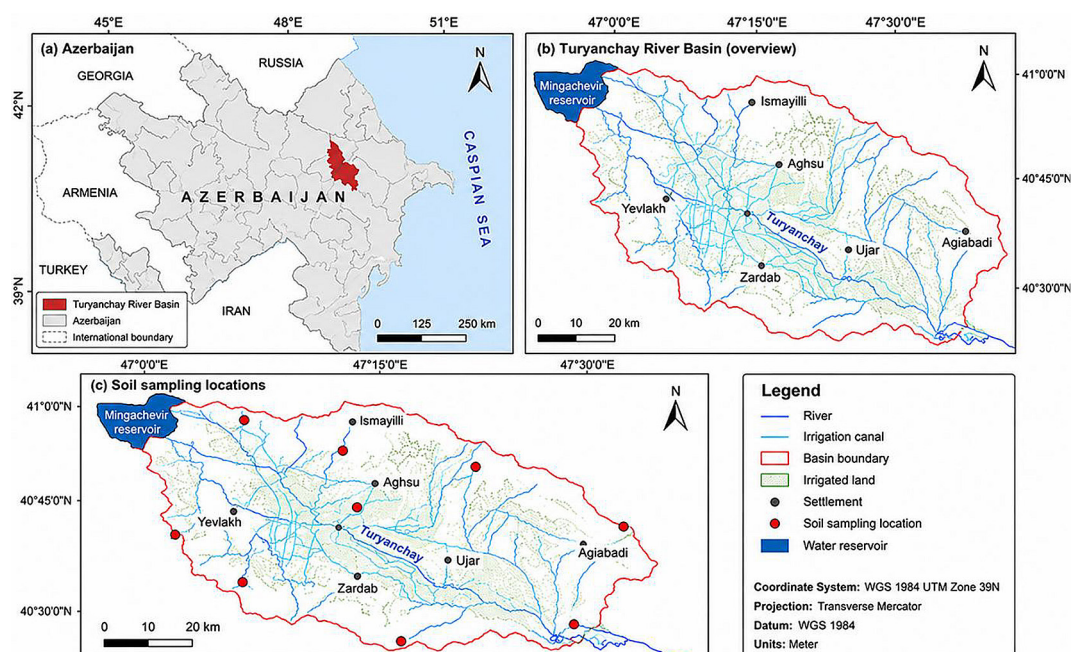


Figure 1. Location of the Turyanchay River basin in Azerbaijan, showing the regional location of the basin (a), the hydrographic network and irrigated areas of the study area (b), and the spatial distribution of the soil sampling locations used for geochemical investigations (c)

correlation with the World Reference Base for Soil Resources (WRB 2014) reported by Babayev et al. (2017), these soils correspond to Calcisols, and Fluvisols, respectively. The investigated soils showed varying degrees of salinity, which were characterized on the basis of the measured dry residue, total soluble salt content, and ionic composition of the soil water extracts. Agricultural land use includes irrigated fields of wheat, barley, rice, and alfalfa, which are subjected to continuous irrigation and associated salinization processes.

Soil sampling and laboratory analysis

Field investigations were carried out across representative agro-landscape units within the middle and lower parts of the Turyanchay River basin. Soil sampling sites were selected to represent differences in geographical location, soil type, land use, salinity conditions, and irrigation status. Samples were collected from depth intervals defined for each investigated soil profile. A total of 22 depth-specific sampling units were included in the geochemical dataset, representing different sampling locations, soil types, and sampling depths.

The sampling locations, geographical coordinates, soil types, and sampling depths of the geochemical dataset are presented in Table 1, while the measured trace-element concentrations are presented in Table 2. Soil samples were collected from the predefined depth intervals described in Table 1, following the general field procedures of the FAO Guidelines for Soil Description (FAO, 2006).

Prior to laboratory analysis, the soil samples were air-dried, homogenized, gently crushed, and passed through a 2-mm sieve. For EDXRF analysis, the <2 mm soil fraction was further finely ground and homogenized to obtain a uniform powder. The prepared soil powder was placed in an XRF sample cup, and the measurement surface was covered with a thin X-ray-transparent film. The samples were analyzed as loose powder without pelletization or pressing.

The laboratory analyses focused on the principal physicochemical properties governing salinity development and geochemical transformation. Soil pH was determined potentiometrically in a 1:1 (w/v) soil-to-distilled-water suspension using a calibrated pH meter. Organic carbon was determined by wet dichromate oxidation using potassium

Table 1. Sampling locations, soil characteristics, and sampling depths in the Turyanchay River basin

Sampling site	Coordinates (WGS 84)	Soil type / land use	Depth (cm)
Yevlakh, Yukhari Garkhun	40°37'6.21"N, 47°11'36.37"E	Grey-brown, irrigated alfalfa	0–10
Yevlakh, Yukhari Garkhun	40°37'6.21"N, 47°11'36.37"E	Grey-brown, irrigated alfalfa	10–50
Yevlakh, Yukhari Garkhun	40°37'6.21"N, 47°11'36.37"E	Grey-brown, irrigated alfalfa	50–120
Yevlakh, Khaldan	40°42'58.24"N, 47°14'12.89"E	Grey soil, saline	0–50
Yevlakh, Khaldan	40°42'58.24"N, 47°14'12.89"E	Grey soil, saline	50–100
Ujar, Garadaghli	40°28'18.65"N, 47°34'13.58"E	Grey-meadow, cultivated field	0–50
Ujar, Garadaghli	40°28'18.65"N, 47°34'13.58"E	Grey-meadow, cultivated field	50–100
Ujar, Khalaj	40°21'9.68"N, 47°40'24.08"E	Grey-meadow, saline	0–50
Ujar, Khalaj	40°21'9.68"N, 47°40'24.08"E	Grey-meadow, saline	50–100
Zardab, Bichagchi	40°17'44.84"N, 47°28'4.09"E	Grey soil, cultivated field	0–10
Zardab, Bichagchi	40°17'44.84"N, 47°28'4.09"E	Grey soil, cultivated field	10–50
Zardab, Bichagchi	40°17'44.84"N, 47°28'4.09"E	Grey soil, cultivated field	50–120
Zardab, Salahli	40°14'11.99"N, 47°41'11.17"E	Grey-meadow, cultivated field	0–50
Zardab, Salahli	40°14'11.99"N, 47°41'11.17"E	Grey-meadow, cultivated field	50–100
Aghdash, Kotavan	40°21'39.78"N, 47°25'51.22"E	Meadow-grey, irrigated alfalfa	0–50
Aghdash, Kotavan	40°21'39.78"N, 47°25'51.22"E	Meadow-grey, irrigated alfalfa	50–100
Aghdash, Khosrov	40°37'14.98"N, 47°34'34.56"E	Grey-brown, saline	0–50
Aghdash, Khosrov	40°37'14.98"N, 47°34'34.56"E	Grey-brown, saline	50–100
Aghdash, Garadeyin	40°30'51.69"N, 47°16'37.56"E	Alluvial-meadow, tugay forest	0–50
Aghdash, Garadeyin	40°30'51.69"N, 47°16'37.56"E	Alluvial-meadow, tugay forest	50–100
Aghdash, Abad	40°27'9.54"N, 47°19'30.40"E	Alluvial-meadow	0–50
Aghdash, Abad	40°27'9.54"N, 47°19'30.40"E	Alluvial-meadow	50–100

dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4), following the Walkley–Black method (Walkley and Black, 1934). The humus content was calculated from the measured organic carbon content using the conventional conversion factor of 1.724 (humus = organic C $\times$ 1.724). Soil salinity was characterized on the basis of the measured dry residue, total soluble salt content, and ionic composition of the soil water extracts (HCO_3^- , Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , and $Na^+ + K^+$).

The selected physicochemical parameters were used to characterize the soil environment controlling salinity development and trace element redistribution under long-term irrigation.

The ionic composition of the soil water extracts (HCO_3^- , Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , and $Na^+ + K^+$) was determined using conventional wet-chemical analytical methods (Page et al., 1982). The soil–water extracts were prepared at a 1:5 (w/v) ratio using distilled water. Bicarbonate (HCO_3^-) was determined by acid titration, chloride (Cl^-) by argentometric titration (Mohr method), sulfate (SO_4^{2-}) using the gravimetric barium sulfate method, calcium (Ca^{2+}) and magnesium (Mg^{2+}) by complexometric titration with EDTA, and sodium plus potassium ($Na^+ + K^+$) by flame photometry. The concentrations of the soluble ions were initially determined in $mg\ L^{-1}$ and subsequently converted to percentages on a dry-soil mass basis for presentation in the corresponding salinity and ionic-composition table. Na^+ and K^+ are reported jointly as $Na^+ + K^+$ in accordance with the original analytical dataset. Trace element concentrations (Br, Fe, Ni, Rb, Sr, As, Y, and Zr) were determined using an ElvaX CEP-01 energy-dispersive X-ray fluorescence (EDXRF) spectrometer. Instrument calibration was performed using certified reference materials (CRMs) and factory-supplied multi-element calibration standards. Analytical quality control included repeated measurements of selected samples, and the analytical precision was generally better than $\pm 5\%$ for major elements and within $\pm 10\%$ for trace elements. Instrumental detection limits varied depending on the element and matrix composition.

Geochemical indices

To quantify the degree of geochemical transformation, two commonly used geochemical indices were calculated: the CF and the I_{geo} . Because site-specific geochemical background values were not available for the investigated

alluvial–proluvial soils, global Clarke values were used as reference values to provide a consistent basis for comparative assessment. Given the lithological heterogeneity of the study area, the calculated indices were interpreted as relative geochemical enrichment indicators, rather than as direct evidence of anthropogenic contamination. Contamination factor (CF):

$$CF = \frac{C_n}{B_n} \quad (1)$$

where: C_n is the measured concentration of the investigated element in the soil sample (%) B_n is the corresponding geochemical background (Clarke) concentration (%).

Geoaccumulation index (I_{geo}):

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5B_n} \right) \quad (2)$$

where: C_n is the measured concentration of the investigated element; B_n is its geochemical background concentration; and 1.5 is the correction factor accounting for natural lithological variability.

The calculated CF and I_{geo} values were interpreted according to the classification schemes proposed by Håkanson (1980) and Müller (1969), respectively:

- For CF, the following classes were used: $CF < 1$, low; $1 \leq CF < 3$, moderate; $3 \leq CF < 6$, considerable; and $CF \geq 6$, very high relative enrichment (Håkanson, 1980).
- For I_{geo} , the following classes were applied: $I_{geo} \leq 0$, unpolluted; $0 < I_{geo} \leq 1$, unpolluted to moderately polluted; $1 < I_{geo} \leq 2$, moderately polluted; $2 < I_{geo} \leq 3$, moderately to strongly polluted; $3 < I_{geo} \leq 4$, strongly polluted; $4 < I_{geo} \leq 5$, strongly to extremely polluted; and $I_{geo} > 5$, extremely polluted (Müller, 1969).

Statistical analysis

Statistical analyses were performed using EViews software

Spearman's rank correlation analysis was applied to evaluate relationships between soil pH, salinity characteristics, major soluble ions, organic carbon, and humus content. Spearman's correlation was used as a non-parametric measure of association; therefore, normality was not assumed as a prerequisite for the correlation analysis. Statistical significance was assessed at $p < 0.05$.

Correlation coefficients were calculated to identify associations among the measured variables, and were interpreted as associations rather than evidence of causal relationships.

The correlation analysis was based on the 22 depth-specific sampling units presented in Table 4. The three replicate measurements within each depth interval were averaged, and the resulting depth-specific mean values were used in the correlation analysis. Thus, the analytical unit was the depth interval, rather than the individual replicate ($n = 22$), and the nested profile structure was not treated as 66 independent observations. Non-detects for trace elements did not enter the correlation matrix presented in Table 5 because this analysis was restricted to the reported soil physicochemical and salinity variables. No formal multiple-testing correction was applied; therefore, the reported p -values were treated as nominal, and the correlation analysis was interpreted as exploratory.

Spatial analysis and mapping

Spatial distribution of trace element associations was evaluated using GIS-based descriptive spatial analysis of the investigated sampling units. The coefficient of variation (C_v , %) was calculated to assess the degree of spatial variability of the investigated elements. The geochemical landscape map was prepared using ArcGIS 10.8 (ESRI, Redlands, CA, USA) by integrating field observations, laboratory analytical results, soil information, and hydrographic features. Spatial delineation of geochemical landscape units was based on the interpretation of measured geochemical characteristics, landscape attributes, and field observations, rather than on mathematical interpolation of point observations. All spatial analyses and cartographic processing were performed using the WGS 84 / UTM Zone 39N coordinate reference system. The resulting map was interpreted as a descriptive geochemical landscape map showing spatial differences in geochemical characteristics and trace-element associations, rather than as an interpolated concentration-prediction surface or as a map of quantitatively defined contamination or micronutrient-deficiency zones.

Conceptual model of soil–water–geochemical interactions

To better illustrate the process-based interactions governing trace element redistribution

under irrigation-induced salinization, a conceptual model was proposed (Figure 2).

The conceptual model illustrates the coupled soil–water–geochemical processes linking irrigation input, evaporation, secondary salinization, soil alkalinization, geochemical reactions, and the spatial redistribution of trace elements in irrigated arid agro-landscapes.

Irrigation with mineralized water represents an important external factor potentially contributing to geochemical transformation. Under arid climatic conditions, intense evapotranspiration promotes evaporative concentration of dissolved salts, resulting in secondary salinization and the formation of salinity gradients within the soil profile.

Increasing salinity modifies soil chemical properties, particularly pH, leading to alkaline conditions that may influence trace element mobility. Under these conditions, some elements may become less mobile through precipitation and adsorption processes, whereas others may remain comparatively mobile or accumulate locally, depending on soil properties and geochemical conditions.

Limited natural drainage, soil texture, and groundwater conditions further restrict downward leaching and promote the spatial redistribution of soluble elements. At the same time, accumulated salts alter soil hydraulic properties, influencing water movement and reinforcing salinity development through positive soil–water feedback mechanisms.

Overall, the conceptual framework demonstrates that trace element redistribution in irrigated arid agro-landscapes results from the interaction of hydrological, pedological, and geochemical processes. Irrigation-induced salinization is considered an important process linking water movement, salt accumulation, soil alkalinization, and trace element redistribution, thereby controlling the long-term evolution of soil geochemical conditions.

Process-based interpretation framework

To ensure consistency between field observations and the conceptual model, the interpretation of results was based on coupled soil–water–salinity interactions. Relationships among irrigation conditions, salinity gradients, soil pH, and trace element distribution were interpreted as interacting processes controlling geochemical transformation and spatial redistribution within irrigated arid agro-landscapes.

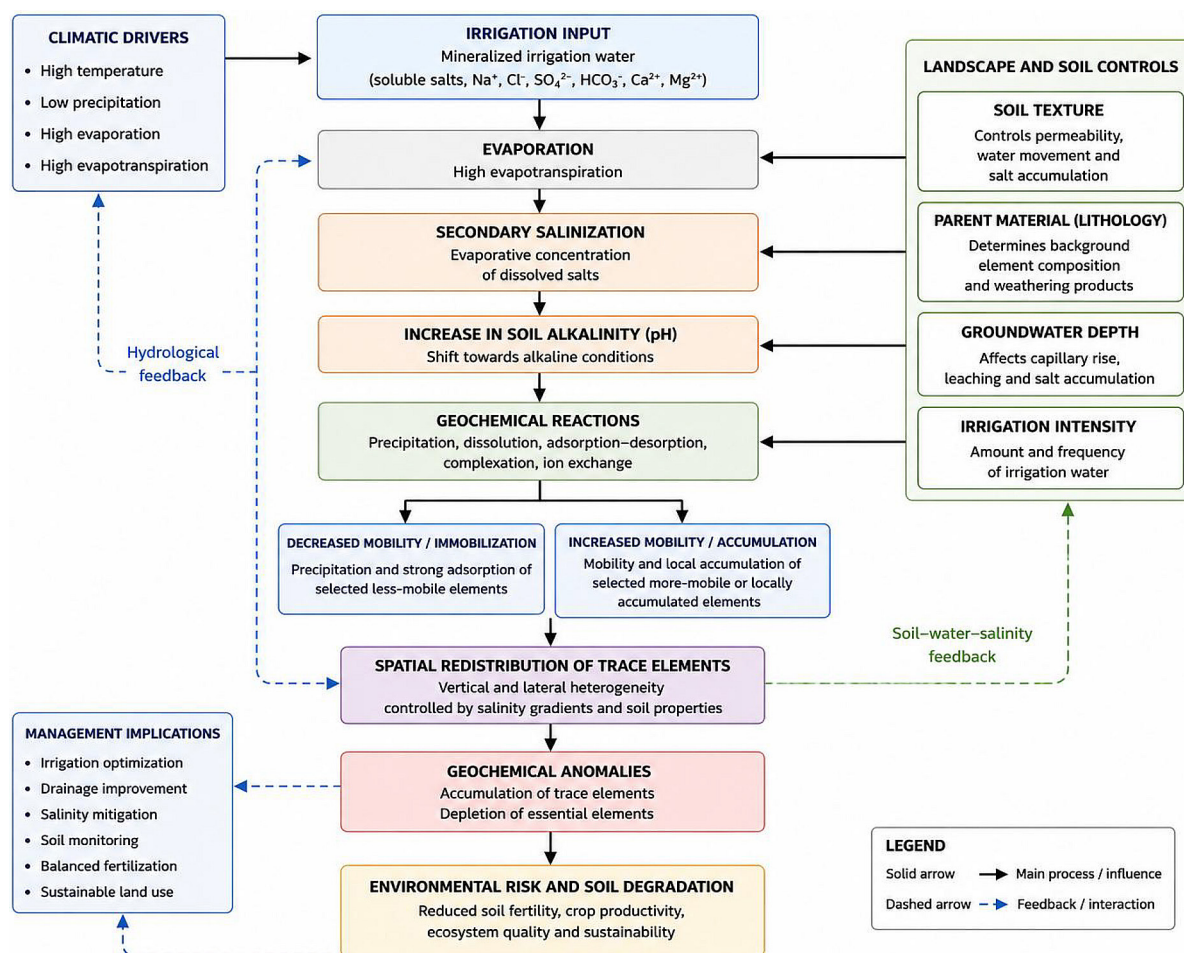


Figure 2. Conceptual model of soil–water–geochemical interactions controlling trace element redistribution under irrigation-induced salinization in arid agro-landscapes

RESULTS

Soil physicochemical properties

The investigated soil profiles exhibited an alkaline reaction, with pH values ranging from 8.2 to 9.0. The consistently alkaline pH values indicate alkaline soil conditions within the investigated agro-landscapes, providing a chemical environment potentially influencing salinity-related geochemical processes and element mobility. Humus and organic carbon contents generally decreased with depth, although profile-specific variations were observed. In the upper soil horizons (0–10 cm), humus content ranged from 1.45 to 2.64%, whereas in the deeper horizons (60–150 cm), it ranged from 0.07 to 0.45%. The ionic composition of the soil water extracts varied considerably among sampling sites and depths. Sulfate (SO_4^{2-}) was the dominant anion in the more saline horizons, whereas Ca^{2+} , Mg^{2+} , and $\text{Na}^+ + \text{K}^+$ showed pronounced spatial and depth-related variability.

Trace element distribution

The concentrations of trace elements measured at different sampling depths are presented in Table 2.

The investigated soil samples contained bromine (Br), arsenic (As), nickel (Ni), iron (Fe), rubidium (Rb), strontium (Sr), yttrium (Y), and zirconium (Zr), although their occurrence and concentrations varied considerably among sampling sites and sampling depths. Br concentrations ranged from 0.0003 to 0.0135%, Fe from 0.0432 to 0.6231%, Rb from 0.0002 to 0.0026%, Sr from 0.0011 to 0.0646%, Y from 0.0002 to 0.0009%, and Zr from 0.0010 to 0.0415%.

Ni was reported only in selected sampling units, with concentrations ranging from 0.0143 to 0.1651%. The highest Ni concentration (0.1651%) occurred at Ujar, Garadaghli at 0–50 cm, followed by Aghdash, Garadeyin at 0–50 cm (0.1359%) and Aghdash, Abad at 50–100 cm (0.1243%).

Table 2. Trace element concentrations in the investigated soil profiles of the Turyanchay River basin at different sampling depths

Sampling site	Depth (cm)	Br (%)	Fe (%)	Ni (%)	Rb (%)	Sr (%)	As (%)	Y (%)	Zr (%)
Yevlakh, Yukhari Garkhun	0–10	0.0052	0.3260	—	0.0012	0.0049	0.0098	—	0.0021
Yevlakh, Yukhari Garkhun	10–50	0.0040	0.1495	—	0.0009	0.0040	0.0038	—	0.0018
Yevlakh, Yukhari Garkhun	50–120	—	0.3300	—	0.0002	0.0036	—	0.0003	0.0018
Yevlakh, Khaldan	0–50	0.0016	0.2248	0.0200	0.0013	0.0061	0.0005	0.0005	0.0022
Yevlakh, Khaldan	50–100	0.0014	0.2604	0.0143	0.0016	0.0052	—	0.0006	0.0025
Ujar, Garadaghli	0–50	0.0096	0.2987	0.1651	0.0018	0.0509	—	0.0006	0.0029
Ujar, Garadaghli	50–100	—	0.2559	0.0317	0.0021	0.0065	—	0.0007	0.0037
Ujar, Khalaj	0–50	0.0032	0.4118	—	0.0015	0.0550	—	0.0009	0.0017
Ujar, Khalaj	50–100	—	0.4417	—	0.0016	0.0377	—	0.0006	0.0010
Zardab, Bichagchi	0–10	0.0135	0.4382	—	0.0018	0.0396	—	0.0004	0.0029
Zardab, Bichagchi	10–50	0.0098	0.4115	—	0.0005	0.0326	—	0.0002	0.0052
Zardab, Bichagchi	50–120	—	0.4881	—	0.0016	0.0392	—	—	0.0019
Zardab, Salahli	0–50	0.0038	0.0432	—	0.0013	0.0037	—	0.0005	0.0032
Zardab, Salahli	50–100	—	0.1999	—	0.0008	0.0029	—	0.0003	0.0019
Aghdash, Kotavan	0–50	0.0047	0.3557	—	0.0016	0.0646	—	0.0006	0.0036
Aghdash, Kotavan	50–100	0.0040	0.4557	—	0.0009	0.0375	—	0.0004	0.0052
Aghdash, Khosrov	0–50	0.0099	0.6231	—	0.0026	0.0144	—	0.0007	0.0036
Aghdash, Khosrov	50–100	0.0092	0.3400	—	0.0018	0.0044	—	0.0004	0.0026
Aghdash, Garadeyin	0–50	0.0025	0.3720	0.1359	0.0016	0.0415	—	0.0005	0.0026
Aghdash, Garadeyin	50–100	0.0003	0.4247	—	0.0023	0.0011	—	0.0005	0.0027
Aghdash, Abad	0–50	0.0041	0.3739	—	0.0016	0.0415	—	0.0005	0.0415
Aghdash, Abad	50–100	0.0003	0.3065	0.1243	0.0018	0.0046	—	0.0009	0.0029

Note: “—” indicates that the element was not reported in the original analytical dataset. Element concentrations are expressed as percentages (%).

As was reported only at Yevlakh, Yukhari Garkhun, and Yevlakh, Khaldan. The highest As concentration (0.0098%) was recorded at Yukhari Garkhun in the 0–10 cm interval, whereas lower concentrations occurred at Yukhari Garkhun at 10–50 cm (0.0038%) and at Khaldan at 0–50 cm (0.0005%). Vertical patterns differed among elements and sampling sites. In several sampling sites, Br concentrations were higher in the upper sampling interval and decreased with depth or were not reported in deeper samples. Fe did not show a uniform depth-related trend: its concentration increased with depth in some sampling sites (e.g., Zardab, Bichagchi, and Aghdash, Kotavan), whereas it decreased in others (e.g., Aghdash, Khosrov and Aghdash, Abad). Sr likewise exhibited marked profile-specific variability.

Overall, the trace-element dataset demonstrates substantial spatial and depth-related heterogeneity, rather than a uniform pattern of surface enrichment. These differences provide the basis for the subsequent assessment of relative geochemical enrichment using CF and Igeo.

Geochemical indices

The calculated contamination factor (CF) geoaccumulation index (Igeo), and coefficient of variation (Cv) for the investigated trace elements are presented in Table 3. Br, As, and Ni showed the highest relative enrichment with respect to the adopted world-soil background values. Ni exhibited the highest contamination factor (CF = 28.23), followed by As (CF = 6.88) and Br (CF = 5.12). Sr showed a comparatively low enrichment (CF = 1.30), whereas Fe, Rb, Y, and Zr had CF values below 1. The corresponding Igeo values were 4.23 for Ni, 2.20 for As, and 1.77 for Br, corresponding to the categories of strongly to extremely polluted, moderately to strongly polluted, and moderately polluted, respectively, according to the adopted Igeo classification. Sr had an Igeo value of –0.20, while Fe, Rb, Y, and Zr showed negative Igeo values ranging from –3.94 to –2.70 and were classified as unpolluted. These classifications indicate relative enrichment with respect to the adopted background values and should not

Table 3. Geochemical indices and coefficients of variation of trace elements in soils of the Turyanchay River basin agro-landscapes

Element	n	Mean (%)	Cv (%)	CF	Igeo	Igeo category
Br	17	0.00512	75.7	5.12	1.77	Moderately polluted
As	3	0.00470	100.3	6.88	2.20	Moderately to strongly polluted
Ni	6	0.08188	82.0	28.23	4.23	Strongly to extremely polluted
Sr	22	0.02280	92.0	1.30	−0.20	Unpolluted
Fe	22	0.34233	36.6	0.10	−3.94	Unpolluted
Rb	22	0.00147	38.3	0.22	−2.79	Unpolluted
Y	18	0.00053	36.1	0.23	−2.70	Unpolluted
Zr	22	0.00452	184.1	0.17	−3.15	Unpolluted

Note: n – number of reported measurements used for each element; Cv – coefficient of variation; CF – contamination factor; Igeo – geoaccumulation index. Unreported/non-detect values (—) were excluded. Mean concentrations and Cv values were recalculated from Table 2. CF and Igeo were calculated from the element-specific mean concentrations using the adopted world-soil background values (mg kg^{−1}): Br 10, As 6.83, Ni 29, Sr 175, Fe 35,000, Rb 68, Y 23, and Zr 267. The background values follow Kabata-Pendias (2011). CF and Igeo indicate relative enrichment with respect to the adopted background and should not be interpreted as direct evidence of anthropogenic contamination.

Table 4. Ionic composition of soil water extracts, dry residue, total soluble salts, and organic matter characteristics of the depth-specific sampling units in the Turyanchay River basin agro-landscapes

Sampling site	Soil type / land use	Depth (cm)	HCO ₃ [−] (%)	Cl [−] (%)	SO ₄ ^{2−} (%)	Ca ²⁺ (%)	Mg ²⁺ (%)	Na ⁺ + K ⁺ (%)	Dry residue (%)	Total salts (%)	Organic carbon, C (%)	Humus (%)
Ujar, Garadaghli village	Grey-meadow soil	0–10	0.018	0.025	0.630	0.120	0.070	0.057	1.129	0.920	1.50	1.59
Ujar, Garadaghli village	Grey-meadow soil	10–50	0.015	0.032	0.549	0.130	0.050	0.043	1.025	0.819	0.84	1.45
Ujar, Garadaghli village	Grey-meadow soil	50–120	0.015	0.007	0.090	0.020	0.020	0.007	0.169	0.159	0.24	0.41
Aghdash, Orta Laki village	Meadow-grey soil	0–10	0.018	0.021	0.075	0.040	0.010	0.002	0.190	0.166	0.48	1.83
Aghdash, Orta Laki village	Meadow-grey soil	10–30	0.015	0.004	0.013	0.010	0.002	0.001	0.047	0.045	0.42	1.72
Aghdash, Orta Laki village	Meadow-grey soil	30–70	0.018	0.004	0.023	0.010	0.002	0.005	0.068	0.062	0.24	0.41
Aghdash, Orta Laki village	Meadow-grey soil	70–120	0.021	0.004	0.004	0.080	0.001	0.001	0.170	0.161	0.17	0.28
Aghdash, Yukhari Laki village	Meadow-grey soil, irrigated alfalfa	0–10	0.037	0.011	0.035	0.020	0.002	0.033	0.140	0.138	0.84	1.45
Aghdash, Yukhari Laki village	Meadow-grey soil, irrigated alfalfa	10–40	0.027	0.009	0.032	0.010	0.007	0.003	0.090	0.088	0.66	1.14
Aghdash, Yukhari Laki village	Meadow-grey soil, irrigated alfalfa	40–100	0.024	0.007	0.012	0.010	0.001	0.002	0.058	0.056	0.26	0.45
Aghdash, Yukhari Laki village	Meadow-grey soil, irrigated alfalfa	100–150	0.024	0.010	0.027	0.030	0.001	0.001	0.096	0.093	0.04	0.07
Zardab, Mammadgasimli village	Grey-meadow soil, Kura area	0–20	0.027	0.012	0.010	0.020	0.002	0.001	0.080	0.069	1.08	1.86
Zardab, Mammadgasimli village	Grey-meadow soil, Kura area	20–40	0.027	0.005	0.009	0.020	0.002	0.001	0.075	0.072	0.76	1.31
Zardab, Mammadgasimli village	Grey-meadow soil, Kura area	40–60	0.033	0.007	0.010	0.020	0.002	0.001	0.076	0.073	0.45	0.78
Zardab, Mammadgasimli village	Grey-meadow soil, Kura area	60–120	0.027	0.009	0.007	0.010	0.002	0.001	0.058	0.056	0.39	0.67
Aghdash, Masad village	Grey-brown soil, pasture	0–10	0.027	0.009	0.055	0.030	0.009	0.001	0.133	0.107	1.53	2.64
Aghdash, Masad village	Grey-brown soil, pasture	10–30	0.027	0.009	0.103	0.040	0.015	0.011	0.229	0.205	1.32	2.28
Aghdash, Masad village	Grey-brown soil, pasture	30–60	0.024	0.010	0.642	0.220	0.064	0.012	1.179	1.177	0.80	1.37
Aghdash, Masad village	Grey-brown soil, pasture	60–72	0.018	0.010	0.382	0.110	0.036	0.010	0.582	0.566	0.26	0.45
Aghdash, Bulagotaghi village	Grey soil, irrigated forage field	0–10	0.034	0.019	0.008	0.001	0.001	0.122	0.108	0.093	1.41	2.43
Aghdash, Bulagotaghi village	Grey soil, irrigated forage field	10–30	0.031	0.010	0.009	0.002	0.001	0.097	0.078	0.073	0.84	1.45
Aghdash, Bulagotaghi village	Grey soil, irrigated forage field	20–60	0.027	0.007	0.007	0.004	0.002	0.073	0.059	0.057	0.78	1.34

Note: all numerical values are reproduced from the original analytical dataset. Ionic concentrations, dry residue, total salts, organic carbon, and humus are expressed as percentages (%).

be interpreted as direct evidence of anthropogenic contamination. The coefficient of variation (Cv) indicated pronounced spatial and depth-related heterogeneity in the distribution of several elements. The highest variability was observed for Zr (Cv = 184.1%), followed by As (100.3%), Sr (92.0%), Ni (82.0%), and Br (75.7%). Lower variability was recorded for Rb (38.3%), Fe (36.6%), and Y (36.1%). Overall, the combined CF, Igeo, and Cv results demonstrate element-specific patterns of relative enrichment and spatial variability across the investigated soils. Ni, As, and Br showed the strongest enrichment relative to the adopted background, whereas the particularly high Cv values of Zr, As, Sr, Ni, and Br indicate substantial heterogeneity among the investigated depth-specific sampling units.

Salinity characteristics

A separate physicochemical dataset comprising 22 depth-specific sampling units was used to characterize soil salinity and organic matter conditions. The ionic composition of soil water extracts, dry residue, total soluble salts, organic carbon, and humus contents for these sampling units are presented in Table 4. The concentrations of HCO_3^- , Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , and $\text{Na}^+ + \text{K}^+$ varied among the investigated depth-specific sampling units. The dry residue ranged from 0.047 to 1.179%, whereas total soluble salts ranged from 0.045 to 1.177%. The highest dry residue and total salt contents were recorded in the 30–60 cm interval at Aghdash, Masad village (1.179 and 1.177%, respectively), while comparatively high values were also observed in the upper intervals at Ujar, Garadaghli village. Organic carbon content ranged from 0.04 to 1.53%, and humus content ranged from 0.07 to 2.64%. The highest organic carbon and humus contents were recorded in the 0–10 cm interval of the Grey-brown pasture soil at Aghdash, Masad village. Differences in the ionic composition, dry residue, total soluble salts, organic carbon, and humus contents were observed among the investigated depth-specific sampling units, indicating substantial spatial and depth-related variability in soil salinity and organic matter characteristics.

Vertical differentiation of soil properties

The investigated soil sampling sites exhibited vertical differences in trace element concentrations.

Br generally showed higher concentrations in the upper sampling intervals and decreased with depth or was not reported in the deeper intervals of several profiles. As was reported only in the samples from Yevlakh (Yukhari Garkhun and Khaldan), with the highest concentration (0.0098%) recorded in the 0–10 cm interval at Yukhari Garkhun. Ni was detected only in selected sampling units and showed profile-specific vertical variation.

Iron (Fe), rubidium (Rb), strontium (Sr), yttrium (Y), and zirconium (Zr) showed variable vertical distributions among the investigated sampling site. Fe concentrations increased with depth in some sampling site but decreased in others, while Sr, Rb, Y, and Zr likewise exhibited profile-specific depth patterns. Overall, the results indicate substantial vertical heterogeneity, rather than a uniform decrease in trace element concentrations with soil depth.

Spatial variability and mapping

The spatial distribution of geochemical landscape units and trace element associations is presented in Figure 3. The map shows spatial differences in the distribution of geochemical landscape units and trace element associations across the investigated agro-landscapes. These mapped units represent descriptive geochemical associations, rather than interpolated concentration surfaces. Associations containing Br, As, Fe, Mn, Zn, Sr, Rb, Y, and Zr were identified in different parts of the study area. Variations in the dominant anions (HCO_3^- , Cl^- , SO_4^{2-}) and cations (Ca^{2+} , Mg^{2+} , Na^+) were also observed among the mapped geochemical units. The distribution of geochemical landscape units differed throughout the investigated area, reflecting spatial heterogeneity in soil salinity, ionic composition, land use, and trace element associations.

Statistical relationships

Spearman's rank correlation matrix of soil chemical properties and salinity indicators ($n = 22$) is presented in Table 5.

Significant correlations were observed among the investigated soil chemical properties and salinity indicators. The strongest positive correlations occurred between dry residue and total soluble salts ($\rho = 0.99$, $p < 0.001$). Strong positive relationships were also observed between organic

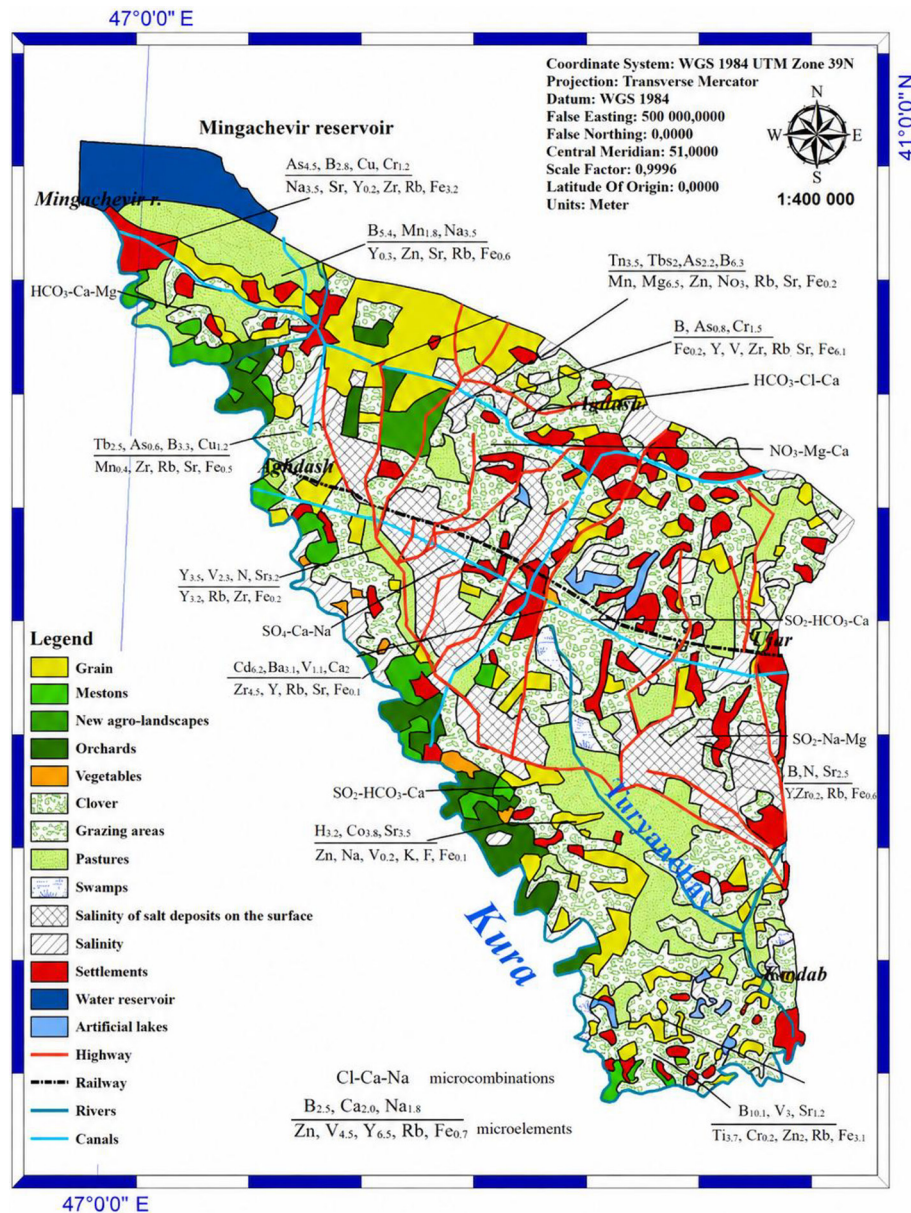


Figure 3. Geochemical landscape map of agro-landscapes in the Turyanchay River basin (Azerbaijan)

carbon and humus ($\rho = 0.89$, $p < 0.001$), SO_4^{2-} and Mg^{2+} ($\rho = 0.84$, $p < 0.001$), Ca^{2+} and total salts ($\rho = 0.82$, $p < 0.001$), and Ca^{2+} and dry residue ($\rho = 0.82$, $p < 0.001$).

Additional significant positive correlations were found between SO_4^{2-} and total salts ($\rho = 0.73$), SO_4^{2-} and dry residue ($\rho = 0.73$), SO_4^{2-} and Ca^{2+} ($\rho = 0.70$), Ca^{2+} and Mg^{2+} ($\rho = 0.66$), Mg^{2+} and dry residue ($\rho = 0.66$), and Mg^{2+} and total salts ($\rho = 0.66$). Cl^- was positively correlated with dry residue ($\rho = 0.59$), total salts ($\rho = 0.55$), and organic carbon ($\rho = 0.55$).

Significant negative correlations were observed between HCO_3^- and SO_4^{2-} ($\rho = -0.46$), HCO_3^- and Ca^{2+} ($\rho = -0.45$), and HCO_3^- and Mg^{2+}

($\rho = -0.45$). These relationships indicate coordinated variation among soluble ions and salinity indicators across the investigated depth-specific sampling units.

DISCUSSION

Irrigation-induced salinization as a key driver

The results suggest that the irrigation-induced salinization is an important factor influencing geochemical transformation within the investigated agro-landscapes. The accumulation of

Table 5. Spearman's rank correlation matrix of soil chemical properties and salinity indicators (n = 22)

Variable	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	Ca ²⁺	Mg ²⁺	Na ⁺ + K ⁺	Dry residue	Total salts	Organic C	Humus
HCO ₃ ⁻	1.00									
Cl ⁻	—	1.00								
SO ₄ ²⁻	-0.46*	0.45*	1.00							
Ca ²⁺	-0.45*	—	0.70***	1.00						
Mg ²⁺	-0.45*	—	0.84***	0.66***	1.00					
Na ⁺ + K ⁺	—	0.47*	—	—	—	1.00				
Dry residue	—	0.59**	0.73***	0.82***	0.66***	—	1.00			
Total salts	—	0.55**	0.73***	0.82***	0.66***	—	0.99***	1.00		
Organic C	0.43*	0.55**	—	—	—	0.44*	—	—	1.00	
Humus	—	0.48*	—	—	—	—	—	—	0.89***	1.00

Note: Values are Spearman's rank correlation coefficients (ρ). Only statistically significant correlations are reported in the lower triangle; — indicates a non-significant correlation ($p \geq 0.05$). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. The analysis was based on the 22 depth-specific sampling units presented in Table 4.

soluble salts, which varied substantially among sampling sites and soil depths, is consistent with the combined effects of long-term irrigation with mineralized water, intense evaporation, and restricted natural drainage. The highest dry residue and total soluble salt contents were recorded in the 30–60 cm interval at Aghdash, Masad village, while comparatively high values also occurred in the upper soil intervals at Ujar, Garadaghli village. These observations are consistent with the conceptual model proposed in this study, in which irrigation represents an important external factor influencing coupled soil–water–geochemical processes (Brady and Weil, 2017; Sposito, 2016).

The observed salt distribution pattern is consistent with the previous investigations conducted in irrigated arid and semi-arid regions, where secondary salinization develops because evapotranspiration substantially exceeds precipitation, resulting in progressive accumulation of soluble salts in the root zone (Corwin, 2021; Cui et al., 2023; Ivushkin et al., 2019; Mukhopadhyay et al., 2021; Setia et al., 2011; Wang et al., 2023). In the present study, the close relationship between dry residue and total soluble salts ($\rho = 0.99$, $p < 0.001$), together with significant positive relationships of SO₄²⁻, Ca²⁺, and Mg²⁺ with these salinity indicators, further supports the coordinated variation of soluble salts across the investigated sampling units.

Similar vertical redistribution of salts has been reported in irrigated agricultural systems of Central Asia, northern China, and the Mediterranean region, where prolonged irrigation alters both soil chemical composition and hydrological

functioning (Chu et al., 2023; Deviren Saygin et al., 2023; Mukhopadhyay et al., 2021; Qadir et al., 2014; Shrivastava and Kumar, 2015). Compared with many previous studies that primarily quantified salinity levels, the present investigation indicated that irrigation-induced salinization forms part of the physicochemical environment associated with the observed spatial and depth-related variability of trace elements. However, the trace-element distributions did not uniformly follow the salinity pattern, indicating that salinity should not be regarded as the sole control on their redistribution. These findings support the view that salinity is an important environmental factor contributing to geochemical differentiation within irrigated arid agro-landscapes together with lithogenic background and local soil–landscape conditions (Corwin, 2021; Mukhopadhyay et al., 2021; Wang Y. et al., 2018).

Control of pH and salinity on trace element mobility

The alkaline soil conditions observed in the investigated agro-landscapes (pH 8.2–9.0) are likely to be among the major factors potentially influencing trace element mobility and redistribution. Increasing soil alkalinity modifies the chemical speciation, adsorption behavior, and precipitation–dissolution equilibria of many trace elements, thereby influencing their mobility and bioavailability. Consequently, the geochemical behavior of individual elements depends on their physicochemical characteristics and their

interactions with saline soil environments (Allo-way, 2013; McBride, 1994; Sposito, 2016).

The relatively low concentrations and low relative enrichment of Fe ($CF = 0.10$; $Igeo = -3.94$) in the present study are consistent with the well-established tendency of Fe to exhibit low solubility under alkaline and oxidizing soil conditions, where Fe oxides and hydroxides are generally stable. Similar behavior has been reported for saline and sodic soils in many arid and semi-arid regions, where increasing soil pH may reduce Fe solubility and plant availability (Brady and Weil, 2017; Kabata-Pendias, 2011; McBride, 1994; Sposito, 2016; Sparks et al., 2023). However, because Fe availability was not directly measured in the present study, the observed low relative enrichment should not be interpreted as direct evidence of micronutrient deficiency.

In contrast, Ni exhibited the highest relative enrichment ($CF = 28.23$; $Igeo = 4.23$), followed by As ($CF = 6.88$; $Igeo = 2.20$) and Br ($CF = 5.12$; $Igeo = 1.77$). This enrichment may be associated with the combined effects of irrigation-related salinity processes, evaporative concentration, limited leaching, and the lithological characteristics of the alluvial–proluvial parent materials under arid climatic conditions. Given the absence of site-specific background values and the limited evidence directly linking the enrichment of these elements to irrigation-induced salinization, the observed CF and $Igeo$ values are interpreted as relative enrichment with respect to the adopted world-soil background values, rather than as definitive evidence of anthropogenic contamination.

The contrasting behavior of Fe, Ni, As, and Br indicates that trace elements respond differently to changes in soil chemical conditions. Overall, the present results suggest that soil salinity and alkalinity may contribute to the physicochemical conditions governing trace element mobility and spatial distribution within the investigated irrigated agro-landscapes, although lithogenic background, element-specific geochemical behavior, and local soil–landscape conditions must also be considered (Huang et al., 2021; Yang et al., 2021).

Spatial heterogeneity and geochemical anomalies

The geochemical landscape map (Figure 3) shows spatial differences in the distribution of trace element associations across the investigated agro-landscapes of the Turyanchay River basin.

The associations containing Br, As, Fe, Sr, Rb, Y, and Zr were identified in several parts of the study area. These mapped associations represent descriptive geochemical landscape units derived from the integration of analytical results, soil characteristics, and field observations rather than interpolated concentration surfaces.

The observed spatial differences are likely to reflect the combined influence of natural landscape characteristics and long-term agricultural activities. Variations in microrelief, irrigation intensity, drainage conditions, parent material, and soil salinity may collectively influence the redistribution and accumulation of trace elements. Consequently, neighboring agricultural fields may exhibit different geochemical characteristics despite being located within the same climatic region. The high coefficients of variation observed for several elements, particularly Zr ($Cv = 184.1\%$), As (100.3%), Sr (92.0%), Ni (82.0%), and Br (75.7%), further demonstrate substantial spatial and depth-related heterogeneity within the investigated dataset.

Comparable spatial patterns have been reported in the irrigated arid regions of Central Asia, northern China, and the Middle East, where irrigation-induced salinization interacts with local geomorphological conditions to produce heterogeneous distributions of trace elements (Cui et al., 2023; Ivushkin et al., 2019; Wang et al., 2023; Wei et al., 2021; Yang et al., 2021). These studies also suggest that anthropogenic factors may enhance the natural geochemical variability of arid landscapes. In the present study, however, the relative contributions of lithogenic and anthropogenic sources cannot be quantitatively separated; therefore, the observed spatial heterogeneity should be interpreted as the combined expression of natural geochemical background and soil–landscape conditions potentially modified by long-term agricultural use.

The spatial distribution observed in the present study suggests that trace element associations occur within a spatially heterogeneous salinity environment in the investigated agro-landscapes, which is consistent with the recent studies combining remote sensing, spatial modeling, and geostatistical analysis of saline soils (Chu et al., 2023; Huang et al., 2021; Webster and Oliver, 2007). Because direct spatial correlations between individual trace elements and salinity indicators were not quantified, the mapped patterns should not be interpreted as evidence of a direct

salinity-controlled relationship. The geochemical landscape map provides a useful basis for identifying the areas with contrasting geochemical characteristics and may support site-specific assessment and management of irrigated agricultural lands.

Soil–water–geochemical interactions

The statistical relationships presented in Table 5 indicate strong associations among the major ions, total soluble salts, dry residue, organic carbon, and humus content in the investigated soils. The very strong positive correlation between dry residue and total soluble salts ($\rho = 0.99$, $p < 0.001$), together with the strong correlations of Ca^{2+} with dry residue and total salts ($\rho = 0.82$, $p < 0.001$), SO_4^{2-} with Mg^{2+} ($\rho = 0.84$, $p < 0.001$), and SO_4^{2-} with dry residue and total salts ($\rho = 0.73$, $p < 0.001$), reflects the close association among the principal components and indicators of soil salinity.

The positive relationships among the major soluble ions suggest that salinity development is accompanied by the changes in the chemical composition of the soil solution. Conversely, the negative correlations of HCO_3^- with SO_4^{2-} ($\rho = -0.46$), Ca^{2+} ($\rho = -0.45$), and Mg^{2+} ($\rho = -0.45$) indicate contrasting patterns in ionic composition among the investigated depth-specific sampling units. Likewise, the strong correlation between organic carbon and humus ($\rho = 0.89$, $p < 0.001$) reflects the close relationship between these indicators of soil organic matter.

The observed statistical relationships are consistent with the conceptual soil–water–geochemical framework proposed in this study, in which irrigation, evaporation, and salt accumulation interact to modify the chemical environment of the soil (Assouline, 2021; Brady and Weil, 2017; Hillel, 2008; Sposito, 2008; Vereecken et al., 2016). However, because the correlation analysis is exploratory and does not establish causal relationships, these associations should be interpreted as evidence of coordinated variation among soil chemical properties, rather than direct proof of process causality.

Although the present statistical analysis primarily describes the relationships among soil chemical properties and salinity indicators, the combined interpretation of the statistical results, geochemical indices, and spatial distribution patterns suggests that soil–water interactions provide an important physicochemical context for

interpreting the geochemical evolution of the investigated irrigated agro-landscapes (Hong et al., 2021; Vogel et al., 2018). Because trace elements were not included in the correlation matrix, the statistical results themselves should not be interpreted as direct evidence of salinity-controlled trace element redistribution.

Process-based interpretation and feedback mechanisms

The results suggest that irrigation-induced salinization is associated with interconnected hydrological and geochemical processes rather than acting as an isolated phenomenon. Irrigation with mineralized water introduces dissolved salts into the soil profile, whereas intense evapotranspiration promotes their redistribution and, under suitable soil–water conditions, accumulation within the soil profile. As a result, soil salinity and alkalinity may progressively increase, influencing both the chemical and physical properties of the soil.

Increasing concentrations of soluble salts may alter soil aggregation, pore continuity, and hydraulic conductivity, thereby potentially affecting infiltration and downward leaching. These processes may promote further salt accumulation within the root zone and contribute to the development of secondary salinization. Similar feedback mechanisms have been reported for irrigated soils in arid and semi-arid environments, where the interactions between soil hydraulic properties and salt transport influence the long-term evolution of soil degradation (Assouline, 2021; Brady and Weil, 2017; Hillel, 2008; Mukhopadhyay et al., 2021).

The geochemical effects of these processes extend beyond salinity development. Progressive alkalization may modify trace element speciation and bioavailability, resulting in different mobility patterns among individual elements. Consequently, irrigation-induced salinization may influence soil chemical composition, nutrient availability, and trace element redistribution, highlighting the close relationship between hydrological processes and geochemical transformation (McBride, 1994; Sposito, 2016; Sparks et al., 2023). In the present study, the pronounced element-specific variability in the CF, Igeo, and Cv values, together with the observed spatial and vertical heterogeneity, is consistent with such differential geochemical behavior, although these data do not establish direct causal links between salinization and individual trace elements.

Overall, the present findings are consistent with the process-based conceptual framework proposed in this study and suggest that long-term irrigation and associated salinity development may contribute to the evolution of the soil–water–geochemical system. The proposed feedback mechanisms should therefore be regarded as a process-based interpretation of the observed patterns rather than as directly measured hydrological fluxes. These interactions should be considered when assessing soil degradation and developing sustainable management strategies for irrigated arid agro-landscapes (Food and Agriculture Organization of the United Nations & United Nations Environment Programme, 2021; Lal, 2015).

Implications for soil management

The findings of this study have important implications for the sustainable management of irrigated soils in arid and semi-arid regions. The observed relative enrichment of several trace elements, particularly Ni, As, and Br, indicates the need for continued monitoring of their concentrations and spatial variability, especially in areas affected by salinization. However, because the enrichment indices were calculated relative to adopted world-soil background values, these results should not be interpreted as direct evidence that prolonged irrigation caused their accumulation or that they represent anthropogenic contamination. At the same time, the low relative enrichment of Fe ($CF < 1$) should be interpreted cautiously because total elemental concentrations alone do not provide direct information on plant-available micronutrient status (Brady and Weil, 2017; Kabata-Pendias, 2011).

The spatial distribution of trace element associations suggests that the soil degradation processes are spatially variable within the Turyanchay River basin. Consequently, uniform management practices may not provide equally effective mitigation across the entire irrigated area. Site-specific management based on the identified geochemical and salinity patterns may therefore support more targeted decisions regarding irrigation scheduling, drainage efficiency, and salinity control (Sun et al., 2022; Wang Q. et al., 2018).

The present results also suggest that regular monitoring of soil salinity, alkalinity, irrigation water quality, and trace element concentrations may improve the assessment of soil degradation in irrigated agro-landscapes. The integration of

descriptive geochemical landscape mapping with routine soil monitoring may facilitate the identification of areas requiring more detailed investigation and support timely management decisions (Shi et al., 2018; Tóth et al., 2016).

From a broader perspective, the integrated methodological framework proposed in this study, combining geochemical indices (CF and Igeo), spatial analysis, statistical evaluation, and the conceptual soil–water–geochemical interaction model, may provide a useful approach for characterizing salinity-associated geochemical variability in other arid and semi-arid regions. The proposed framework may therefore contribute to the development of soil conservation strategies and sustainable irrigation management under increasing climate and water-resource pressures (Food and Agriculture Organization of the United Nations & United Nations Environment Programme, 2021; Lal, 2015; Sun et al., 2022).

CONCLUSIONS

This study presented a spatial and process-based assessment of trace element redistribution in relation to salinity conditions in the Turyanchay River basin, one of the representative irrigated arid agro-landscapes of Azerbaijan. The integration of geochemical indices, statistical analyses, spatial mapping, and a conceptual soil–water–geochemical interaction model enabled an assessment of the processes potentially associated with geochemical transformation in saline agricultural soils.

The principal findings of the study can be summarized as follows:

1. Irrigation-induced salinization is an important factor associated with geochemical transformation and trace element redistribution within the investigated agro-landscapes. Long-term irrigation with mineralized water, together with intense evaporation and limited natural drainage, may contribute to the accumulation of soluble salts and the development of pronounced salinity gradients.
2. Soil salinity and alkalinity provide an important physicochemical context potentially influencing trace element mobility. Fe showed low relative enrichment ($CF = 0.10$; $I_{geo} = -3.94$), whereas Ni exhibited the highest relative enrichment ($CF = 28.23$; $I_{geo} = 4.23$), followed by As ($CF = 6.88$; $I_{geo} = 2.20$) and

Br (CF = 5.12; Igeo = 1.77). These values indicate enrichment relative to the adopted world-soil background and should not be interpreted as direct evidence of anthropogenic contamination. Spatial analysis showed considerable variation in trace element distribution across the study area. The associations containing Br, As, Fe, Sr, Rb, Y, and Zr, together with the high coefficients of variation observed for several elements, indicate substantial spatial and depth-related heterogeneity in geochemical characteristics within the basin. The descriptive geochemical landscape map identified areas with contrasting geochemical associations without implying interpolated concentration patterns.

3. The combined application of geochemical indices (CF and Igeo), GIS-based descriptive spatial analysis, and statistical evaluation provided a useful framework for identifying areas with contrasting geochemical characteristics and assessing salinity-associated geochemical variability. The proposed conceptual soil–water–geochemical interaction model provides a process-based framework for interpreting the relationships among irrigation, salinity development, alkalization, and trace element redistribution. The conceptual framework is consistent with the observed spatial and statistical patterns obtained in the present study, although the proposed interactions should be interpreted as process-based explanations, rather than directly measured causal relationships.

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