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Ecological and Ameliorative Assessment of Soil Salinization in the Shirvan Plain, Kura-Araz Lowland, Azerbaijan

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ABSTRACT

The Kura-Araz Lowland is one of the most important agricultural regions of Azerbaijan and plays a significant role in crop production and national food security. This study evaluates the current ecological and ameliorative status of irrigated soils in the Kurdamir and Goychay districts of the Shirvan Plain. For the first time, a comparative assessment of irrigated soils was conducted in the villages of Sor-Sor in Kurdamir District and Chakhirli and Inca in Goychay District. The salinity dynamics of the past two years were examined using six representative soil sections established in characteristic landscape and agricultural areas. Soil samples were collected from depths of 0–25, 25–50, 50–75, 75–100, 100–150, and 150–200 cm and analyzed for physicochemical properties, salinity status, and productivity-related indicators, including exchangeable (absorbed) bases. The results indicate that the soils of both districts are predominantly heavy-textured, carbonate-rich throughout the soil profile, and alkaline in reaction. Soil pH ranged from 7.18 to 7.53 in Kurdamir and from 7.04 to 8.13 in Goychay. Salinity was identified as the principal soil constraint limiting agricultural productivity in both districts. Grain yields in Kurdamir ranged from 3.0 to 5.0 t ha^{-1}, while cotton yields ranged from 2.8 to 3.0 t ha^{-1}. In Goychay, grain

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productivity ranged from 3.0 to 3.2 t ha^{-1}. The findings demonstrate that irrigation-induced salinization and associated soil degradation require systematic monitoring and improved irrigation and soil-management practices to maintain soil fertility, enhance agricultural productivity, and ensure the long-term sustainability of irrigated agriculture in the Shirvan Plain.

Keywords: Soil Salinization; Agriculture; Ameliorative Issues; Irrigated Soils; Soil Fertility; Plain; Lowland

1. Introduction

Agriculture has historically played a fundamental role in Azerbaijan's economy owing to the country's favorable climatic conditions, diverse landscapes, and fertile land resources. For decades, these advantages have supported the cultivation of a wide range of agricultural crops and contributed significantly to the development of domestic agriculture [1]. However, in recent decades, a combination of global, regional, and local challenges-including population growth, the gradual degradation of pasturelands, increasing pressure on water resources, ecological and environmental degradation, climate variability, and the growing frequency of natural hazards—has imposed new constraints on agricultural production and food security [2]. In response to these challenges, Azerbaijan has implemented substantial reforms aimed at increasing agricultural productivity, promoting efficient and sustainable resource management, and strengthening the national food supply system. Consequently, the agricultural sector has undergone significant modernization and has become an increasingly important component of the country's sustainable development strategy [3,4].

Agricultural production in Azerbaijan is highly dependent on irrigation, as a large proportion of cultivated land is concentrated in the country's lowland regions, which generally range from approximately 28 m below sea level to 100 m above sea level. These lowland areas are predominantly characterized by arid and semi-arid subtropical climatic conditions. High levels of solar radiation, prolonged sunshine duration, and favorable temperature regimes provide a long growing season, enabling the cultivation of two crops per year in some agricultural areas and, under favorable conditions, even three crops. However, intensive irrigation in these regions also increases the risk of secondary salinization, soil degradation, and deterioration of soil fertility, particularly under conditions of inadequate drainage and inefficient water management.

The Kura-Araz Lowland, characterized by a long growing season, high solar radiation, and extensive irrigated agricultural lands, represents one of the most important agricultural regions of Azerbaijan. The region encompasses several agroecological zones with considerable variation in soil properties, climatic conditions, hydrological regimes, and land-use patterns. These differences strongly influence soil fertility, agricultural productivity, and the development of degradation processes. Therefore, the assessment and monitoring of the ecological and ameliorative conditions of irrigated soils in the Kura-Araz Lowland are essential for developing sustainable land-management practices, maintaining soil productivity, and ensuring long-term agricultural and food security.

However, the long-term, intensive, and environmentally unsustainable use of land resources has contributed to declining soil fertility, accelerated salinization, and the intensification of various forms of soil degradation. These processes have adversely affected the agrophysical and agrochemical properties of soils, reduced their ecological and productive potential, and consequently resulted in substantial declines in agricultural land productivity in several areas of the region [5].

In this context, the sustainable and efficient management of land and water resources is essential for maintaining agricultural productivity under changing environmental conditions, protecting soil resources, and strengthening food security. In particular, in irrigated agricultural areas, the efficient use of irrigation water, the construction and maintenance of effective drainage systems, and the implementation of scientifically based land-reclamation measures are critical for preventing soil degradation and restoring and enhancing the productive capacity of agricultural lands. Such approaches contribute not only to the conservation of natural resources but also to the long-term sustainability and resilience of agricultural production [6].

The protection, restoration, and sustainable management of soil resources represent some of the most critical environmental challenges of the twenty-first century. Numerous studies have demonstrated that soils worldwide are increasingly exposed to anthropogenic pressures, resulting in significant changes in their physicochemical and biological properties. Deforestation and shrub removal, uncontrolled grazing, and inadequate implementation of soil-conservation and appropriate agrotechnical practices have collectively accelerated soil degradation processes [7,8].

Sustainable agricultural development requires the balanced utilization of natural resources, improvement of soil productivity, and scientifically based spatial planning of agricultural production [9]. Effective agricultural land management cannot be achieved without a comprehensive assessment of the natural and socioeconomic conditions of individual regions. Azerbaijan is characterized by abundant natural resources and a highly diverse soil cover, reflecting a complex pattern of soil formation influenced by climatic conditions, vegetation, geomorphological characteristics, and hydrological processes. Variations in granulometric composition, salinity, alkalinity, erosion intensity, and the degree of soil development contribute to considerable spatial heterogeneity in soil properties across the country [10].

Effective reclamation and sustainable management of degraded soils are essential for maintaining stable and high agricultural productivity. In arid and semi-arid regions, where natural drainage is often inadequate, improper irrigation practices and poor maintenance of irrigation and drainage infrastructure can accelerate soil degradation and eventually render cultivated lands unsuitable for agricultural production. Prolonged agricultural use under such conditions may further reduce soil organic matter as a result of accelerated humus mineralization, thereby negatively affecting soil fertility and productive capacity [11].

Soil salinization and alkalization are among the major environmental constraints to agricultural development in Azerbaijan. These processes are particularly widespread in the Kura-Araz Lowland, where a substantial proportion of agricultural land is affected by varying degrees of salinity. Approximately 60% of the 2.2 million hectares of land in the region is reported to be affected by moderate salinity. Similar soil degradation problems are observed in the Siyazan–Sumgait region, the Ajinohur–Jeyranchol massif, and several areas of the Nakhchivan Autonomous Republic. At the national level, approximately 1.326 million hectares, or about 15.4% of Azerbaijan's total territory, are affected by soil salinization to varying degrees [12,13].

Although salinization and alkalization may develop under natural conditions, their intensity and spatial extent have been considerably increased by anthropogenic activities, particularly inappropriate irrigation, inadequate drainage, and inefficient land management. If appropriate reclamation measures are not implemented in a timely manner, these processes can significantly reduce agricultural productivity and adversely affect natural ecosystems, including lowland forests and pasture communities. Therefore, saline and alkaline soils should be regarded as environmentally vulnerable land resources requiring systematic reclamation and management. Key measures include the development and proper maintenance of drainage systems, controlled leaching of soluble salts, physicochemical amelioration, and the implementation of appropriate land-management and regulatory practices to reduce degradation and restore soil productivity [14].

The occurrence and development of soil salinization and groundwater-related processes in the Kura-Araz Lowland are strongly influenced by the region's distinctive natural, hydrological, geographical, geological, and hydrogeological conditions. Limited natural drainage, together with the shallow occurrence of groundwater across extensive areas, promotes the accumulation and upward movement of groundwater, particularly under intensive irrigation regimes [15]. Another important characteristic of the region is the relatively high proportion of sodium in the soil exchange complex and groundwater composition. This condition contributes to the development of soil alkalization and sodification processes and may further deteriorate soil structure and hydraulic properties.

Inadequately designed or poorly managed reclamation practices may also contribute to secondary salinization, increased soil alkalinity, and the formation of surface soil crusts. Therefore, the reclamation of saline and alkaline soils requires an integrated approach that combines efficient irrigation-water management, effective drainage, controlled leaching, and scientifically justified chemical and physicochemical amelioration measures. Such an integrated strategy is essential for restoring soil fertility, improving the productive capacity of degraded lands, and ensuring the long-term sustainability of irrigated agriculture in the Kura-Araz Lowland [16].

The main objective of this study is to assess the ecological and reclamation status of soils in the Kurdamir and Goychay districts of the Shirvan Plain. The study area represents one of the major agricultural regions of the Kura–Araz Lowland and is characterized by extensive irrigated agriculture. The research examines the current condition of the soils, identifies the principal factors contributing to soil degradation, evaluates their reclamation potential, and determines the major challenges associated with soil reclamation. The results are intended to provide a scientific basis for developing sustainable soil-management strategies and implementing appropriate measures to improve soil quality, restore soil fertility, and enhance agricultural productivity within the study area [17].

The Shirvan Plain is one of the most important agricultural regions of the Kura-Araz Lowland in Azerbaijan. Favorable topographic conditions, relatively long growing seasons, and an extensive irrigation network have supported intensive agricultural production in the region for several decades. However, prolonged irrigation and deficiencies in water-management practices have contributed to the development and expansion of soil salinity in many parts of the plain. In particular, excessive irrigation, inadequate drainage, and the shallow occurrence of groundwater have promoted the accumulation of soluble salts within the soil profile, resulting in deterioration of soil properties, reduced fertility, and limitations on agricultural productivity [18].

The Shirvan Plain extends along the left bank of the Kura River, from the Mingachevir Reservoir toward the foothill zones of the Langebiz, Boyuk Harem, and Kichik Harem mountain ranges. The plain covers an area of approximately 859.7 thousand hectares and includes agricultural lands within the administrative territories of Agdash, Goychay, Ujar, Zardab, Kurdamir, and Agsu districts. Its extensive agricultural potential, combined with increasing pressure from salinization and other land-degradation processes, makes the Shirvan Plain an important area for studying the ecological condition of irrigated soils and evaluating reclamation requirements and management options [19].

2. Research Object and Methodology

This study investigated the soils of agricultural lands in Sor-Sor village of Kurdamir District and Chakhirly and Inje villages of Goychay District, located within the Shirvan Plain of the Kura-Araz Lowland, Azerbaijan. The selected sites are of considerable agricultural importance and are characterized by recurring soil degradation and reclamation challenges associated with arid and semi-arid environmental conditions and long-term irrigation. The study was designed to assess the ecological and ameliorative status of the soils and to identify the principal soil properties and degradation processes affecting their agricultural productivity.

Field investigations were conducted in Sor-Sor village of Kurdamir District and Chakhirly and Inje villages of Goychay District. Four soil sections were established in Sor-Sor village within agricultural fields cultivated with different crops and characterized by relatively similar geomorphological, parent-material, and lithological conditions. The selected soil sections were located in fields under cotton and cereal production. To evaluate temporal changes in soil properties and monitor the dynamics of soil conditions at the same sites, repeated soil samples were collected from the established sections in October 2025 and March 2026.

In Chakhirly village, Goychay District, one soil section was established in a cotton field in March 2026. A second soil section was established in a cereal field in Inje village during the same period. These sampling sites enabled a comparative assessment of the morphological and physicochemical characteristics of soils under different agricultural land-use conditions. The geographical coordinates, site characteristics, and other relevant field information for the soil sections established during the study are presented.

Soil samples collected from the established profiles were analyzed using standard laboratory procedures to determine their principal physicochemical and agrochemical properties. The carbonate content was determined as $CaCO_3$ using calcimetric and titrimetric methods. Soil particle-size distribution (granulometric composition) was determined using the N. A. Kachinsky pipette method. Cation exchange capacity (CEC) and the composition of exchangeable (absorbed) cations were determined according to the D. Ivanov method.

Hygroscopic moisture was determined gravimetrically by drying the soil samples at 105 °C. Soil reaction (pH) was measured potentiometrically in a 1:5 soil-to-water suspension using a calibrated pH meter. Different forms of soil nitrogen were also analyzed, including exchangeable ammonium nitrogen using the Kononov method, water-soluble ammonia using the Nessler method, and nitrate nitrogen (NO_3^-) using the Grandval-Lajoux method.

Representative soil samples were collected from selected research sites that reflected the dominant soil characteristics and prevailing agricultural conditions of the study area. The geographical coordinates of each soil section were recorded using a Global Positioning System (GPS), providing accurate spatial information for site identification, mapping, comparative analysis, and future monitoring of changes in soil conditions [20,21].

The collected soil samples were analyzed in the Ecology Laboratory of Azerbaijan State University of Economics using modern standard methods commonly applied in soil science and land-reclamation studies in Azerbaijan. Laboratory analyses included the determination of dry residue (total soluble salts), soil reaction (pH), exchangeable cations, absorbed bases, and other physicochemical properties relevant to the assessment of soil fertility and reclamation status under arid and semi-arid subtropical conditions [22].

Particular attention was given to the assessment of soil salinity as a key indicator of the reclamation condition of the investigated soils. The degree of salinization and the predominant types of soluble salts responsible for soil degradation were determined based on the results of laboratory analyses. The obtained data were used to characterize the intensity and distribution of salinity within the studied soil profiles and to evaluate its potential effects on soil fertility, agricultural productivity, and the sustainable use of irrigated agricultural lands [23,24].

The integration of field observations, GPS-based spatial information, repeated soil sampling, and laboratory analyses provided a comprehensive basis for evaluating the morphological, physicochemical, and agrochemical properties of the investigated soils. These data also enabled an assessment of their ecological and ameliorative condition and the identification of the principal soil constraints associated with long-term irrigated agriculture in the study area.

3. Results and Discussion

Effective mitigation of soil salinization in irrigated agricultural lands depends largely on the proper design, operation, and maintenance of irrigation systems and collector–drainage networks. Regular maintenance of irrigation canals, drainage channels, and hydraulic structures is essential for ensuring efficient water distribution, controlling groundwater levels, and preventing the accumulation of soluble salts within the root zone. Field observations and previous studies have demonstrated that properly functioning drainage systems can facilitate the removal of saline groundwater and excess salts from the soil profile, thereby reducing soil salinity to acceptable levels [25].

Soil salinity in the Shirvan Plain exhibits considerable spatial variability. In most areas, the soluble salt content within the upper one-meter soil layer ranges from approximately 0.15% to 3.0%. The highest levels of salinity, reaching approximately 2–3%, are generally observed in river alluvial fan areas. Considerable differences in the intensity and spatial distribution of salinization have also been identified between the western and eastern parts of the Shirvan Plain, reflecting variations in groundwater conditions, soil properties, topography, and irrigation regimes [26].

The hydrogeological characteristics of the Shirvan Plain play an important role in determining the reclamation status of agricultural lands and the effectiveness of reclamation measures. Groundwater hydrogeochemical conditions are influenced by several sources, including river water originating from northern drainage basins and foothill areas, return flows from irrigation systems, and irrigation water that infiltrates into the soil profile. Although groundwater is generally deeper in the northern and foothill zones, its mineralization increases considerably toward the central parts of the plain. Groundwater mineralization in these areas may range from approximately 25–50 g/L to 50–100 g/L [27].

The hydrogeochemical composition of groundwater is controlled by both natural hydrological processes and anthropogenic factors, particularly the operational characteristics of irrigation and drainage systems. Therefore, the implementation of integrated reclamation approaches based on coordinated management of soil, surface water, and groundwater resources is essential for controlling salinization and maintaining the productive capacity of irrigated lands [28].

The presence of highly mineralized groundwater at shallow depths is one of the principal factors contributing to soil salinization in the Shirvan Plain. Groundwater depth varies considerably across the region depending on topography, lithological structure, hydrological conditions, and irrigation intensity. In some areas, groundwater occurs relatively close to the soil surface. Where groundwater is present at depths of approximately 1.5–3.0 m, capillary rise can facilitate the upward movement of dissolved salts into the upper soil horizons. Under the arid climatic conditions of the region, high evaporative demand further intensifies this process, resulting in the concentration and accumulation of salts within the root zone. Over the long term, these processes may cause secondary salinization, deteriorate the agrophysical and agrochemical properties of soils, and ultimately restrict their suitability for agricultural production [29,30].

Gray soils (*Calcisols*) are among the dominant soil types of the Kura-Araz Lowland. The morphological characteristics and physicochemical properties of these soils differ considerably from those of gray soils developed under the climatic and geomorphological conditions of Central Asia and northern Iran. The principal characteristics of the gray soils of the Kura-Araz Lowland include relatively low humus content, limited cation-adsorption capacity, and a high carbonate content. Organic matter is concentrated primarily in the upper soil horizons, whereas carbonate accumulation generally increases in the deeper parts of the soil profile. Sodium-bearing salts are also common, while the granulometric composition is predominantly medium to heavy clay. These textural characteristics strongly influence soil structure, permeability, water movement, and the susceptibility of soils to salinization and alkalization.

Table 1 presents the results of the analysis of the granulometric composition of a soil sample taken from the Sor-Sor village of the Kurdamir region. It is also clear from the table that the soils are heavy and medium clay soils [31].

Table 1. Granulometric composition of soils in the experimental plot of Sor-Sor village, Kurdamir district.

№ of Soil Section	Depth, cm Genetic Layers	Particle Diameter, mm						
		1–0.25	0.25–0.05	0.05–0.01	0.01	0.005–0.001	<0.001	<0.01
1	0–30	0.72	1.49	2.72	9.47	5.56	17.44	62.6
2	30–57	2.23	4.57	3.28	10.9	9.52	23.68	55.92
3	57–92	1.36	2.24	3.46	7.82	16.32	18.8	50
4	92–120	1.5	13.57	2.36	6.92	11.08	10.48	54.09
5	120–150	0.41	1.05	1.68	7.92	9.44	18.12	61.48
6	150–170	0.75	5.93	2.76	2.49	14.68	17.32	57.07
7	170–200	0.35	3.13	3.32	8.49	14.6	10.86	59.25

Table 1 presents the granulometric analysis showed that the soils of the Sor-Sor experimental plot are predominantly composed of fine particles. The content of the physical clay fraction (<0.01 mm), which is an important indicator of soil texture, varied from 50.00% to 62.60% throughout the soil profile. According to these values, the soils can be classified as heavy clay to clay loam textured soils, indicating a high capacity for water retention but also a greater susceptibility to salinization under improper irrigation and drainage conditions [32].

The highest proportion of physical clay (62.60%) was observed in the 0–30 cm surface layer, while the lowest value (50.00%) occurred in the 57–92 cm layer. Nevertheless, the physical clay content remained above 50% in all horizons, confirming the generally heavy texture of the profile.

The coarse sand fraction (1–0.25 mm) represented only a small proportion of the soil granulometric composition, ranging from 0.35% to 2.23% throughout the studied profile. This indicates a limited contribution of coarse particles to the overall texture of the investigated soils. The fine sand fraction (0.25–0.05 mm) ranged from 1.05% to 13.57%, with the highest content recorded in the 92–120 cm horizon.

The silt fraction (0.05–0.01 mm) showed relatively limited variation throughout the soil profile, ranging from 1.68% to 3.46%. Among the finer fractions, particles with a diameter of 0.01–0.005 mm accounted for 2.49–10.90%, whereas the 0.005–0.001 mm fraction ranged from 5.56% to 16.32%. The clay fraction (<0.001 mm) constituted a considerable proportion of the granulometric composition, ranging from 10.48% to 23.68%. Its maximum content was observed in the 30–57 cm horizon, indicating the relative accumulation of fine-dispersed particles within this layer.

Overall, the granulometric analysis indicates that the soils of the Sor-Sor area are characterized by a predominance of fine-dispersed fractions and a relatively high content of physical clay. This textural composition has a substantial influence on the water-physical properties of the soils, particularly their permeability, infiltration capacity, and the movement of water through the soil profile. The high proportion of fine particles can restrict infiltration and internal drainage, thereby increasing the potential for waterlogging and the accumulation of soluble salts under irrigated conditions. Consequently, the development and proper maintenance of effective drainage systems, together with scientifically regulated irrigation regimes adapted to the hydro-physical properties of the soils, are essential for maintaining soil fertility and preventing the intensification of salinization processes.

Analysis of the exchangeable-base composition indicates that the soil-absorbing complex is dominated by calcium and magnesium cations. The total amount of absorbed bases (TAB) ranged from 30.40 to 40.60 mg-eq per 100 g of soil. These values indicate a relatively high capacity of the soil-absorbing complex to retain exchangeable cations and nutrients, which is an important characteristic for maintaining soil fertility (**Table 2**).

Table 2. Determination of the composition and amount of bases absorbed in experimental field soils.

№ of Soil Section	Depth, cm	Mg.eq.			SAB, mg.eq.	%			pH
		Ca	Mg	Na		Ca	Mg	Na	
1	0–25	9	21	1.4	31.4	28.66	66.87	4.47	7.51
2	25–50	8.5	21	1.3	30.8	27.59	66.87	3.6	7.53
3	50–75	7.95	22.45	1.5	30.4	26.15	73.84	4.94	7.46
4	75–100	19.9	19.4	1.3	40.6	49.02	47.78	3.2	7.18
5	100–150	14.4	21.6	1.2	37.2	38.7	58.06	3.24	7.24
6	150–200	11.9	20.2	1.4	33.5	35.22	60.29	4.49	7.24

Calcium was the predominant exchangeable cation throughout the studied soil profile. Its content ranged from 7.95 to 19.90 mg-eq per 100 g of soil, accounting for 26.15–49.02% of the total absorbed bases. The highest calcium content was recorded in the 75–100 cm horizon. The elevated concentration of calcium in this layer suggests a relative accumulation of calcium within the middle portion of the soil profile, while its continued predominance indicates that calcium remains the principal component of the exchangeable-base complex.

The content of exchangeable magnesium ranged from 19.40 to 22.45 mg-eq per 100 g of soil, accounting for 47.78–73.84% of the total absorbed bases. Magnesium was the dominant exchangeable cation in most horizons of the studied soil profile, with its highest relative proportion (73.84%) recorded at a depth of 50–75 cm. The pronounced predominance of magnesium may reflect the mineralogical composition of the parent material and the influence of hydrogeochemical processes associated with long-term irrigation on soil formation and the distribution of exchangeable cations.

Exchangeable sodium occurred in relatively low concentrations, ranging from 1.20 to 1.50 mg-eq per 100 g of soil and representing 3.20–4.94% of the total absorbed bases. These values are considerably lower than those typically associated with sodic or strongly sodium-affected soils. Therefore, no substantial accumulation of exchangeable sodium in the soil-absorbing complex was detected under the current conditions, suggesting that the present risk of soil sodification is relatively low.

The pH of the soil solution varied from 7.18 to 7.53 throughout the studied profile, indicating a predominantly neutral to weakly alkaline soil reaction. The highest pH value (7.53) was recorded in the 25–50 cm horizon, whereas the lowest value (7.18) occurred at a depth of 75–100 cm. The observed pH range generally represents favorable conditions for the growth of most agricultural crops and supports the availability and uptake of essential plant nutrients.

Results demonstrate that the exchangeable-base complex of the investigated soils is dominated by calcium and, particularly, magnesium, whereas exchangeable sodium occurs at relatively low concentrations. The neutral to weakly alkaline soil reaction, together with the relatively high content of absorbed bases, indicates generally favorable agrochemical conditions for agricultural use. Nevertheless, continued monitoring of soil salinity, groundwater hydrogeochemical characteristics, and irrigation practices is necessary to identify potential salt accumulation within the soil profile and to assess the risk of increasing exchangeable sodium under long-term irrigated agriculture.

The analysis of water-soluble salts revealed considerable variation in salinity indicators among the investigated soil profiles. The dry residue content, used as an indicator of the total concentration of water-soluble salts, ranged from 0.10% to 0.93%, indicating differences in the degree and vertical distribution of salinity within the study area (**Table 3**).

Table 3. Salt content of the experimental area soils located in Sor-Sor village of Kurdamir district.

№ of Soil Sections	Depth, cm	%							Dry Residue, %	Dry Residue, %
		CO_3	HCO_3	Cl	SO_4	Ca	Mg	Na+k		
Section-1 Grain (October, 2025)	0–25	Not anal.	0.048	0.028	0.125	0.020	0.009	0.003	0.12	0.22
	25–50		0.012	0.014	0.036	0.025	0.003	0.002	0.09	0.10
	50–70		0.048	0.021	0.125	0.020	0.003	0.004	0.11	0.21
	75–100		0.036	0.021	0.156	0.040	0.003	0.051	0.31	0.37
	100–150		0.036	0.021	0.384	0.060	0.009	0.125	0.64	0.75
	150–200		0.036	0.028	0.084	0.055	0.003	0.003	0.71	0.77
Section-2 Grain (April, 2026)	0–25	Not anal.	0.043	0.071	0.120	0.045	0.011	0.090	0.47	0.50
	25–50		0.055	0.053	0.225	0.050	0.014	0.075	0.47	0.58
	50–70		0.058	0.036	0.138	0.043	0.017	0.030	0.32	0.34
	75–100		0.052	0.071	0.162	0.048	0.015	0.059	0.41	0.43
	100–150		0.049	0.053	0.123	0.040	0.012	0.042	0.32	0.34
	150–200		0.046	0.071	0.244	0.057	0.017	0.082	0.52	0.54
Section-3 Cotton (October, 2025)	0–25	Not anal.	0.048	0.035	0.204	0.035	0.012	0.075	0.41	0.58
	25–50		0.048	0.035	0.144	0.045	0.003	0.052	0.33	0.62
	50–70		0.046	0.071	0.244	0.057	0.017	0.082	0.52	0.65
	75–100		0.049	0.053	0.123	0.040	0.012	0.042	0.33	0.49
	100–150		0.036	0.021	0.084	0.050	0.003	0.495	0.69	0.76
	150–200		0.036	0.021	0.384	0.060	0.009	0.125	0.63	0.85
Section-4 Cotton (March, 2026)	0–25	Not anal.	0.036	0.021	0.156	0.040	0.003	0.051	0.31	0.47
	25–50		0.048	0.035	0.204	0.035	0.012	0.075	0.40	0.60
	50–70		0.036	0.021	0.384	0.060	0.009	0.125	0.64	0.80
	75–100		0.036	0.021	0.084	0.060	0.009	0.495	0.65	0.93
	100–150		0.048	0.048	0.204	0.051	0.012	0.076	0.43	0.56
	150–200		0.036	0.021	0.156	0.040	0.003	0.051	0.31	0.41

In Section 1, located in a field cultivated with cereal crops, the dry residue content generally increased with soil depth. In the upper horizons, its values ranged from 0.10% to 0.22%, whereas at depths below 100 cm, they increased to 0.75–0.77%. These results indicate relatively low salt concentrations in the upper part of the soil profile and a greater accumulation of soluble salts in the deeper horizons. The ionic composition of the water-soluble salts was dominated by chloride (Cl^-) and sulfate (SO_4^{2-}) anions, together with sodium (Na^+) and potassium (K^+) cations.

In Section 2, also located in a cereal-cultivated field, dry residue values ranged from 0.34% to 0.58%, indicating low to moderate levels of salinity. The chloride concentration reached 0.244% in the deepest horizon, suggesting a tendency toward salt accumulation in the lower part of the soil profile. The relatively elevated concentration of sodium may indicate the influence of irrigation water and groundwater on the hydrochemical regime and vertical distribution of soluble salts within the soil profile (**Figure 1**).

Section 3, located in a cotton field, exhibited higher salinity levels than the cereal-cultivated profiles. The dry residue content ranged from 0.49% to 0.85%, with the maximum value of 0.85% recorded at a depth of 150–200 cm. This distribution indicates considerable accumulation of water-soluble salts in the deeper horizons. The increased concentrations of chloride and sulfate anions, together with sodium, indicate a predominantly chloride–sulfate type of salinization. If these salts migrate upward into the root zone through capillary rise or other water-mediated processes, their accumulation may adversely affect plant water uptake and nutrient availability and consequently reduce crop productivity.

The highest salinity indicators among the investigated profiles were recorded in Section 4, which was also located in a cotton field. Dry residue content ranged from 0.41% to 0.93%, with the maximum value (0.93%) occurring at a depth of 75–100 cm. The increasing concentrations of chloride, sulfate, and sodium along the profile indicate intensified salt accumulation, particularly within the middle and lower horizons. This accumulation may be associated with insufficient leaching of soluble salts from the soil profile and restricted drainage conditions (**Figure 1**).

Chloride (Cl^-) and sulfate (SO_4^{2-}) were the predominant water-soluble anions, while sodium (Na^+) and potassium (K^+) represented the principal cations. Carbonate ions were either absent or present at very low concentrations, while bicarbonate (HCO_3^-) concentrations remained relatively low. The predominance of chloride and sulfate ions indicates that the investigated soils are primarily characterized by a chloride–sulfate type of salinization. This pattern is consistent with the development of salinity in irrigated soils under the arid and semi-arid climatic conditions of the Kura-Araz Lowland.

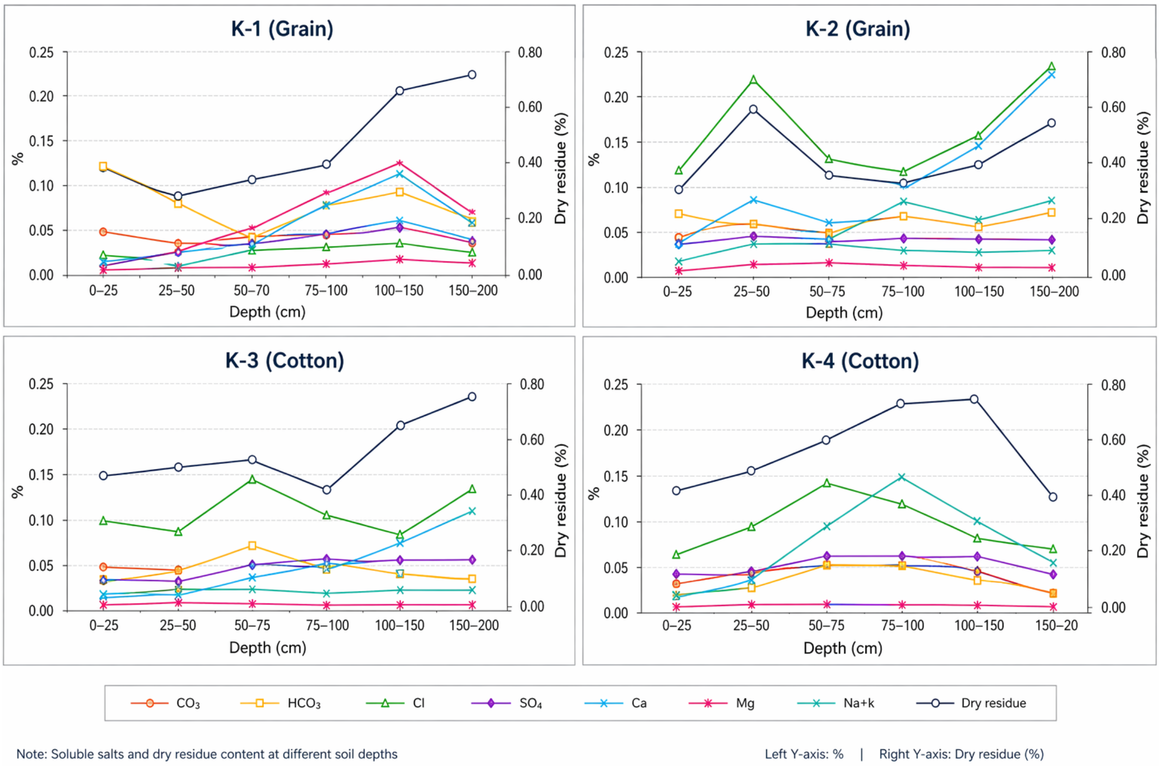

Figure 1. Diagram of salt content change in the Kurdamir district research area.

The results demonstrate substantial spatial and vertical variability in soil salinity at the Sor-Sor experimental site. In several profiles, the concentration of water-soluble salts increased with depth, indicating the accumulation of salts in the subsoil. Salinity levels were generally higher in the cotton fields than in the cereal-cultivatedfields.

Monitoring and laboratory analyses of the soils in Goychay District confirmed relatively high concentrations of water-soluble salts in both investigated areas. The total content of soluble salts, expressed as dry residue, ranged from 0.91% to 2.23%, indicating that the soils are affected by moderate to strong degrees of salinization. The observed salinity levels demonstrate the significant influence of irrigation, evaporation, and groundwater conditions on the accumulation and distribution of soluble salts within the soil profile.

In Chakhirly village (Soil Section 5), the dry residue content ranged from 0.91% to 2.23%. The highest salinity level (2.23%) was recorded in the surface horizon (0–25 cm), whereas the lowest value (0.91%) was observed in the deeper 56–72 cm horizon. The pronounced accumulation of soluble salts in the upper soil layer may be associated with intensive evaporation and the capillary upward movement of saline groundwater. Under the arid climatic conditions of the region, these processes can promote the concentration of soluble salts near the soil surface and increase the risk of adverse effects on plant growth and soil fertility.

The chloride concentration reached 1.188% in the investigated profile, indicating substantial accumulation of chloride salts. In contrast, sulfate concentrations were relatively low, ranging from 0.020% to 0.040%. Among the exchangeable and water-soluble cations, magnesium and sodium–potassium ions were predominant. The predominance of chloride among the soluble anions, together with the observed cation composition, indicates that the soil is primarily affected by a chloride-dominated salinity pattern

(**Table 4**; **Figure 2**). These findings emphasize the need for effective drainage, appropriate irrigation management, and regular monitoring of soil and groundwater salinity to prevent further deterioration of the soil profile and maintain agricultural productivity.

In the Inca village grain field (Soil Section 8), the dry residue values ranged from 1.89% to 1.99%, indicating a consistently high degree of salinity throughout the profile. Chloride concentrations varied from 1.128% to 1.188%, while sulfate content ranged between 0.075% and 0.125%. The relatively uniform distribution of salts with depth suggests long-term salt accumulation under irrigated agricultural conditions. The high concentration of sodium and potassium ions further confirms the dominance of readily soluble salts in the soil solution.

The geographic coordinates of the soil sections were shared in **Table 5**.

Comparison of the two sites shows that the meadow soil of Chakhirli village exhibits greater variability in salt distribution, whereas the cultivated soil of Inca village maintains a uniformly high salinity level throughout the profile. In both cases, chloride ions represent the major anionic component, while magnesium and sodium-potassium ions dominate the cationic composition. Carbonates were not detected, and bicarbonate concentrations remained relatively low, indicating that the salinity is mainly associated with neutral salts rather than alkaline salts (**Figure 3**).

The soils of the Goychay district are characterized by moderate to strong chloride-dominated salinity, with total soluble salt contents considerably higher than those observed in the Sor-Sor area of Kurdamir district. Such salinity levels can significantly reduce agriculture productivity, soil physico-chemical properties, and limited water cover. Therefore, the performance of persuasive drainage systems, annual drain irrigation, groundwater flush custodian, and scientifically based on recovery method is the basic for reducing salt growth and establish the sustainability using system of these cultivation lands (**Figure 4**).

Table 4. Salt content in experimental field soils located in Goychay district.

№ of Soil Section	Depth, cm	%							Total Salts, %	Dry Residue, %
		CO_3	HCO_3	Cl	SO_4	Ca	Mg	Na+k		
Chakhirli village (cotton) Soil section-5 (March) 2026	0–25	Not assigned	0.024	0.070	1.188	0.020	0.102	0.325	2.00	2.23
	25–38		0.012	0.056	1.185	0.025	0.111	0.391	1.78	1.87
	38–56		0.024	0.035	1.176	0.020	0.141	0.267	1.67	1.90
	56–72		0.024	0.021	0.552	0.040	0.015	0.235	0.87	0.91
Inca village (grain field) Soil section-8 (April) 2026	0–27	Not assigned	0.024	0.035	1.152	0.105	0.069	0.330	1.73	1.92
	27–39		0.012	0.042	1.164	0.085	0.054	0.388	1.75	1.89
	39–67		0.012	0.075	1.188	0.075	0.051	0.431	1.83	1.97
	67–68		0.012	0.007	1.128	0.125	0.081	0.292	1.43	1.99

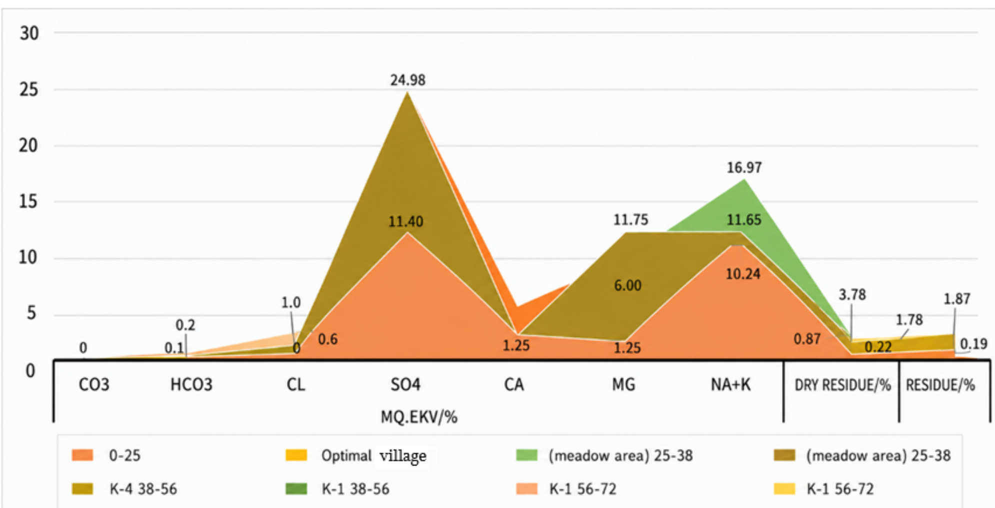

Figure 2. Diagram of salt changes in experimental field soils in the village of Chaxirli.

Table 5. Sections of geographic coordinates in soil sections.

	Number of Section	X Coordinate (East Lenght)	Y Coordinate (North Width)
1	Section 1	X.46°2′49.431″ E	Y.40°44′28.922″ N
2	Section 2	X.46°1′59.110″ E	Y.40°44′33.185″ N
3	Section 3	X.46°2′26.520″ E	Y.40°44′35.287″ N
4	Section 4	X.46°2′49.088″ E	Y.40°44′57.959″ N
5	Section 5	X.46°1′38.303″ E	Y.40°45′10.860″ N
6	Section 8	X.46°2′8.298″ E	Y.40°45′57.008″ N

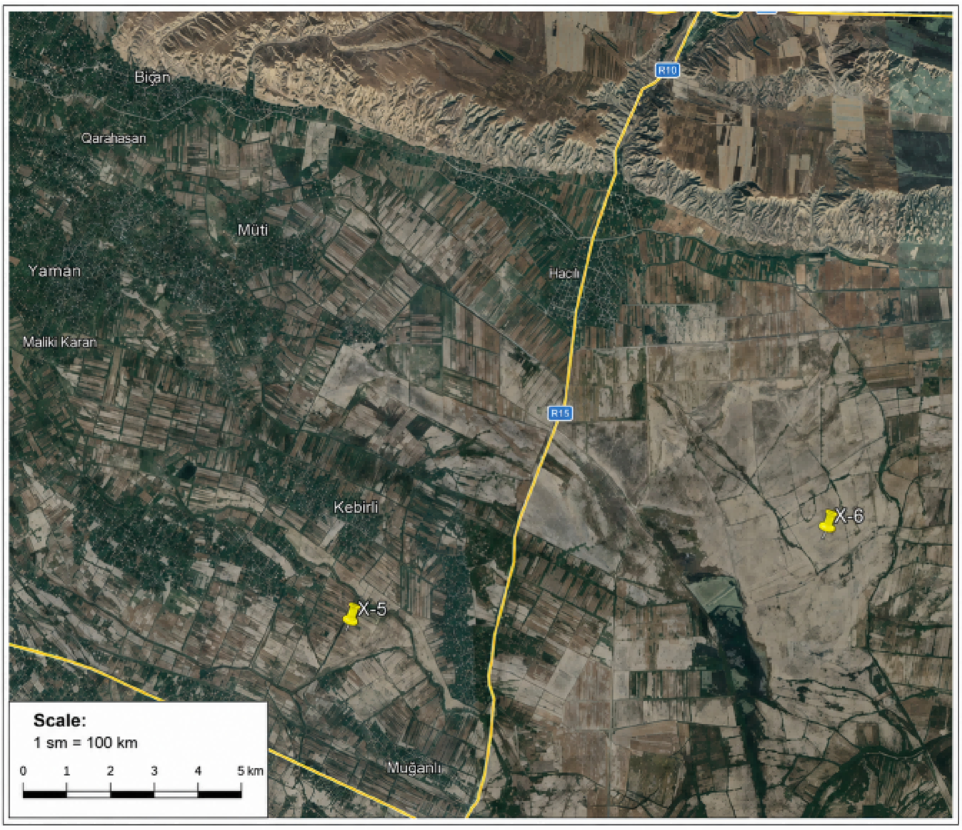

Figure 3. Soil sections and their coordinates within the research area (Soil sections 5 and 8).

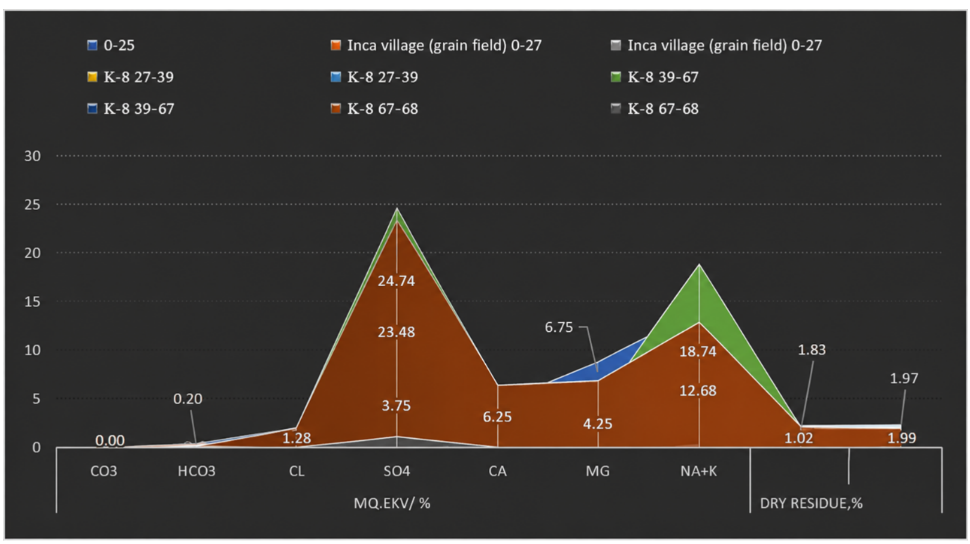

Figure 4. Diagram of salt changes in experimental field soils in Inje village.

4. Conclusion

The soils investigated in the Shirvan Plain and adjacent areas of the Kura–Araz Lowland are predominantly characterized by a heavy granulometric composition and a high proportion of physical clay. In most of the studied profiles, the physical clay content exceeded 50%. Such a texture can restrict water infiltration and internal drainage because of the relatively low hydraulic conductivity of heavy-textured soils. Under inadequate irrigation and drainage conditions, these properties may promote the accumulation and retention of water-soluble salts within the soil profile and increase the risk of secondary salinization.

The predominance of calcium and magnesium in the soil-absorbing complex, together with the relatively low proportion of exchangeable sodium, indicates that the degree of sodification is currently relatively limited. Nevertheless, continued irrigation and the presence of saline groundwater may alter the ionic composition of the soil-absorbing complex over time. Therefore, monitoring exchangeable sodium, groundwater mineralization, and other indicators of sodification remains important for assessing the long-term reclamation status of the soils.

The salt regime of the investigated soils was evaluated based on the results of water-soluble salt analyses. The soils of the experimental sites in Sor-Sor village were generally characterized by low to moderate levels of salinity. In contrast, the soils investigated in Goychay District showed comparatively higher salinity levels, with the total concentration of water-soluble salts exceeding 2% in some samples. In both study areas, chloride (Cl^-) and sulfate (SO_4^{2-}) were the predominant anions, while sodium (Na^+) and magnesium (Mg^{2+}) were among the dominant cations. This ionic composition indicates the development of predominantly chloride–sulfate type salinization in the investigated soils.

The results demonstrate that soil salinization and disruption of the soil salt regime represent major ecological and reclamation constraints to the sustainable development of irrigated agriculture in the Shirvan Plain and the wider Kura–Araz Lowland. In particular, inappropriate irrigation practices applied to heavy-textured soils with restricted water permeability can accelerate the accumulation of soluble salts and intensify soil degradation. The risk is further increased where groundwater is shallow and highly mineralized and where drainage systems are inadequate or poorly maintained.

To mitigate these processes, integrated soil and water-management measures are required. These should include the adoption of efficient irrigation technologies, optimization of irrigation rates and application schedules according to soil and crop requirements, rehabilitation and proper maintenance of existing collector–drainage systems, and the application of seasonal leaching practices where technically and environmentally appropriate. Regular monitoring of soil salinity, groundwater depth and mineralization, exchangeable sodium, and other key reclamation indicators is also necessary to identify emerging degradation processes at an early stage.

The implementation of scientifically based and integrated reclamation measures can reduce the risk of secondary salinization, maintain soil fertility, restore degraded land, and support the long-term sustainable use of irrigated agricultural lands in the Shirvan Plain and Kura–Araz Lowland.

Author Contributions

Conceptualization, L.Z.J. and R.A.S.; methodology, S.A.G.; software, S.M.A.; validation, A.A.J., A.B. and R.A.S.; formal analysis, R.A.S. and S.M.A.; investigation, S.A.G.; resources, L.Z.J. and R.A.S.; data curation, R.A.S.; writing—original draft preparation, L.Z.J.; writing—review and editing, L.Z.J. and R.A.S.; visualization, S.M.A.; supervision, A.A.J. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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