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Article

Linking Ionic Composition to Salinity-Driven Soil Degradation in Arid Agroecosystems of Uzbekistan

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Abstract: Soil salinization is a major environmental process driving land degradation in arid ecosystems, significantly altering soil chemical balance and ecosystem stability. This study investigates ionic composition and salinity-induced soil degradation processes in arid soils of the Bukhara region, Uzbekistan, with a focus on understanding the mechanisms governing soil quality decline. Soil samples collected from the 0–30 cm layer were analyzed for electrical conductivity (ECe), pH, organic matter content, macro-nutrients, and detailed ionic composition using standard agrochemical methods and energy-dispersive X-ray fluorescence (EDXRF). The results revealed moderate to very high salinity levels (5.20–8.12 dS/m) and slightly alkaline conditions (pH 7.6), indicating unfavorable chemical environments for sustainable soil functioning. Ionic analysis confirmed the dominance of sodium (Na^+) and chloride (Cl^-) ions, indicating chloride-type salinization. Elevated sodium concentrations contribute to soil structural degradation, reduced permeability, and disruption of nutrient exchange processes. Despite moderate organic matter content (~1.07%), soils exhibited low total nitrogen and potassium levels, along with critically low available phosphorus, reflecting severe nutrient imbalance under salinity stress. This study provides new insights into salinity-driven soil degradation processes in arid regions and contributes to the development of sustainable land management strategies in Central Asian dryland ecosystems.

Keywords: Soil salinization; Ion exchange; Soil degradation mechanisms; Sodium hazard; Chloride dominance; Nutrient depletion; Arid land soils; Soil chemical imbalance; Central Asia.

Introduction

Soil salinization is one of the most widespread forms of land degradation in arid and semi-arid regions, posing a serious threat to soil productivity, ecosystem stability, and sustainable land use [1]. The accumulation of soluble salts in the soil profile leads to significant physicochemical changes, including increased osmotic pressure, ion toxicity, and disruption of nutrient cycling processes. These changes ultimately reduce soil fertility and limit the long-term productivity of agricultural and natural ecosystems [2].

In arid environments such as Central Asia, salinity development is strongly influenced by high evaporation rates, low precipitation, and insufficient natural leaching of salts from the soil profile [3]. Under these conditions, sodium (Na^+) and chloride (Cl^-) ions tend to accumulate in the upper soil layers, leading to the formation of chloride-type salinity, which is considered one of the most harmful forms due to its direct toxic effects on soil structure and plant physiological processes [4].

The Bukhara region of Uzbekistan represents a typical arid ecosystem where soil salinization processes are widely observed. The combination of climatic aridity and anthropogenic factors, such as irrigation practices and inadequate drainage systems, accelerates salt accumulation and contributes to progressive soil degradation [5]. In such environments, understanding the ionic composition of soils is essential for identifying the mechanisms of salinity development and its impact on soil quality [6].

Soil fertility in saline environments is not determined solely by total nutrient content but is highly dependent on the availability and balance of essential ions, including nitrogen, phosphorus, potassium, calcium, and magnesium [7]. Excess sodium in particular can displace essential cations from soil exchange sites, thereby reducing nutrient availability and degrading soil structure. This ionic imbalance plays a critical role in long-term soil degradation processes [8].

Despite increasing global attention to salinity issues, detailed studies focusing on ionic interactions and their role in soil degradation processes in arid soils of Central Asia remain limited [9]. Most previous research has primarily focused on salinity levels or plant responses, while the underlying chemical mechanisms of soil degradation have not been sufficiently addressed [10].

Therefore, the objective of this study is to investigate the ionic composition and salinity-induced soil degradation processes in arid soils of the Bukhara region, Uzbekistan [11]. The study aims to provide a better understanding of how ionic interactions contribute to soil quality decline and to support the development of effective soil management strategies in saline environments [12].

Materials and methods

Study area

The study was conducted in the Bukhara region of Uzbekistan, which is characterized by an arid continental climate, low annual precipitation, high evaporation rates, and widespread soil salinization. These environmental conditions make the region highly susceptible to salt accumulation and soil degradation processes. The investigated sites represent typical arid agricultural landscapes affected by varying degrees of salinity.

Soil samples were collected from the upper soil layer (0–30 cm depth), which represents the most active zone for nutrient exchange and salt accumulation. Sampling was carried out from different points within each study site, including the beginning, middle, and end of the selected areas, to ensure spatial representativeness. Composite samples were prepared by thoroughly mixing subsamples from each location.

All samples were air-dried at room temperature, gently crushed, and passed through a 1 mm sieve before laboratory analysis.

Laboratory analysis

Soil samples were analyzed in the Republican Soil Analysis Laboratory using standard agrochemical and physicochemical methods. Soil salinity was determined by measuring electrical conductivity (ECe) in a soil-water extract (1:5 ratio). Soil reaction (pH) was measured using a calibrated pH meter in a soil suspension.

Organic matter content (humus) was determined using standard oxidation methods. Total nitrogen was analyzed using the Kjeldahl method, while available forms of nitrogen (NO_3^-), phosphorus (P_2O_5), and potassium (K_2O) were determined using conventional agrochemical extraction procedures.

The ionic composition of soil extracts was determined using an Energy Dispersive X-ray Fluorescence Spectrometer (EDXRF):

Instrument: Rigaku NEX CG

Country of origin: Japan

System type: Polarized EDXRF analytical system

This non-destructive analytical technique was used to determine the elemental and ionic composition of soil samples, including major cations (Na^+, Ca^{2+}, Mg^{2+}, K^+) and anions (Cl^-, SO_4^{2-}, HCO_3^-). The method ensured high precision and reproducibility of results.

All obtained data were processed using standard statistical and agrochemical interpretation methods. Soil parameters were evaluated according to international classification scales for salinity and fertility status. Ionic relationships and salinity indices were analyzed to identify patterns of soil degradation under arid conditions.

The main focus of this study was to assess the relationship between ionic composition and soil degradation processes, particularly the role of sodium and chloride ions in altering soil physicochemical properties and nutrient availability.[13]

Results.

Soil salinity and pH characteristics

Soil salinity and reaction (pH) are key indicators determining soil suitability for plant growth and nutrient availability. The results of the present study showed considerable variation in electrical conductivity (ECe) between the investigated sites. As presented in Table 1, ECe values ranged from 5.20 to 8.12 dS/m, indicating a transition from moderate to very high salinity levels. According to standard salinity classification, both samples belong to chloride-type saline soils, which are characterized by the dominance of chloride and sodium ions and are known to exert strong osmotic stress on plants.

The highest salinity level (8.12 dS/m) was recorded in soils collected near the cut *Rosa canina L.* plants, suggesting a more severe accumulation of soluble salts in this area. In contrast, the second sampling site showed relatively lower salinity (5.20 dS/m), although it still exceeded the threshold for non-saline soils.

Soil reaction (pH) remained stable at 7.6 in both samples, indicating slightly alkaline conditions. This value is above the optimal pH range for *Rosa canina L.* cultivation (6.0–7.0), which may reduce the availability of essential nutrients such as phosphorus, iron, and zinc. The combination of elevated salinity and alkaline reaction suggests unfavorable chemical conditions for plant development and nutrient uptake.

The Table 1. results demonstrate that soil salinity and alkalinity act as limiting factors for *Rosa canina L.* growth in the studied area.[14]

Table 1. Soil salinity (ECe) and pH of soils under Rosa canina L. Plantations.

Sample No.	**Sampling location**	**Electrical conductivity (ECe), dS/m**	**Salinity type and degree**	**Soil pH**	**Soil reaction**	**Optimal pH range for *Rosa canina L.***
1	Soil collected near cut *Rosa canina L.* plants	8.12	Chloride-type, very strongly saline soil	7.6	Slightly alkaline	6.0–7.0
2	Soil collected near mature *Rosa canina L.* plants	5.20	Chloride-type, moderately saline soil	7.6	Slightly alkaline	6.0–7.0

Organic matter status

Soil organic matter is an important indicator of soil fertility, influencing nutrient availability, microbial activity, and overall soil structure stability. The results of the present study showed that humus content in the investigated soils was nearly uniform across the sampling sites. As presented in Table 2, humus content ranged from 1.071% to 1.072%, which corresponds to a medium level of organic matter supply according to agrochemical classification standards.

The calculated organic carbon content (Corg) was 0.623% in both samples, indicating a stable but moderate carbon pool in the studied soils. Although this level is considered acceptable for semi-arid soils, it is insufficient to support optimal nutrient cycling under saline conditions without additional biological or organic inputs.

The Table 2. results suggest that soil organic matter status is relatively stable but not high enough to compensate for nutrient losses caused by salinity stress.

Table 2. Soil organic matter (humus) and organic carbon content.

Sample No.	Sampling location	Humus content (%)	Organic carbon (Corg, %)	Soil fertility level	Reference range for humus (%)
1	Soil collected near cut *Rosa canina L.* plants	1.071	0.623	Medium	0.91–1.35
2	Soil collected near mature *Rosa canina L.* plants	1.072	0.623	Medium	0.91–1.35

Nitrogen status

Soil nitrogen status is a key indicator of soil fertility and plant productivity, especially in saline environments where nutrient cycling is often disrupted. The results of the present study showed that total nitrogen content in both soil samples was low, ranging from 0.072% to 0.074%, indicating poor reserves of organic nitrogen in the soil system.

In contrast, the content of nitrate nitrogen ($N–NO_3$), which represents the mobile and plant-available form of nitrogen, was relatively high, ranging from 68.0 to 71.5 mg/kg. This suggests active mineralization processes and rapid conversion of organic nitrogen into inorganic forms, which is typical for arid and semi-arid soils.

However, despite the relatively high nitrate content, the overall nitrogen balance remains unstable due to the low total nitrogen pool. This imbalance may lead to short-term nitrogen availability but insufficient long-term fertility, especially under conditions of salinity stress.

Table 3. the results indicate that nitrogen availability in the studied soils is characterized by low total reserves but temporarily high mobile forms.

Table 3. Nitrogen forms in soils under Rosa canina L. plantations.

Sample No.	Sampling location	Total nitrogen (%)	Nitrogen status	Nitrate nitrogen ($N–NO_3$, mg/kg)	Availability level	Reference range ($N–NO_3$, mg/kg)
1	Soil collected near cut *Rosa canina L.* plants	0.072	Low	71.5	High	30–50
2	Soil collected near mature *Rosa canina L.* plants	0.074	Low	68.0	High	30–50

Phosphorus status

Phosphorus is one of the essential macronutrients that plays a key role in root development, energy transfer, and reproductive growth of plants. In saline and alkaline soils, phosphorus availability is often limited due to fixation processes involving calcium and other cations.

The results of the present study showed that total phosphorus content in the investigated soils ranged from 0.160% to 0.165%, which corresponds to a medium level of phosphorus reserves. However, the content of available phosphorus (P_2O_5) was low in both samples, ranging from 16.0 to 19.0 mg/kg, which is significantly below the optimal range required for normal plant development (46–60 mg/kg).

The observed low availability of phosphorus despite moderate total content suggests strong chemical fixation of phosphorus under slightly alkaline and saline soil conditions. This limits phosphorus mobility and reduces its uptake efficiency by *Rosa canina L.* plants.

Table 4. phosphorus deficiency in plant-available forms represents a critical limiting factor for plant growth in the studied soils.

Table 4. Phosphorus forms and availability in soils under Rosa canina L. plantations.

Sample No.	Sampling location	Total phosphorus (%)	Fertility level	Available phosphorus (P_2O_5, mg/kg)	Availability status	Reference range (P_2O_5, mg/kg)
1	Soil collected near cut *Rosa canina L.* plants	0.165	Medium	19.0	Low	46–60
2	Soil collected near mature *Rosa canina L.* plants	0.160	Medium	16.0	Low	46–60

Potassium status

Potassium is a key macronutrient involved in enzyme activation, osmoregulation, and plant resistance to abiotic stresses, particularly salinity and drought. In the studied soils, potassium content showed a clear deficiency pattern.

The results indicated that total potassium content ranged from 0.54% to 0.57%, which is classified as very low according to agrochemical standards. The content of available potassium (K_2O) varied from 178.2 to 240.8 mg/kg, which is below the optimal range required for normal plant growth (301–400 mg/kg).

The lowest level of available potassium was observed in the soil collected near cut *Rosa canina L.* plants (178.2 mg/kg), while slightly higher values were recorded in the second sampling site (240.8 mg/kg). Despite this difference, both samples remain potassium-deficient.

Such low potassium availability may be associated with soil salinity and ion competition, particularly the dominance of sodium ions, which can inhibit potassium uptake by plants.

Table 5. potassium deficiency represents a major limiting factor for plant growth and stress tolerance in *Rosa canina L.* plantations in the studied area.

Table 5. Potassium content in soils under Rosa canina L. plantations.

Sample No.	Sampling location	Total potassium (%)	Fertility level	Available potassium (K_2O, mg/kg)	Availability status	Reference range (K_2O, mg/kg)
1	Soil collected near cut *Rosa canina L.* plants	0.54	Very low	178.2	Very low	301–400
2	Soil collected near mature *Rosa canina L.* plants	0.57	Very low	240.8	Low–medium	301–400

Ionic composition of soil water extracts

The ionic composition of soil water extracts provides important information about salinity type, toxicity, and soil chemical balance. The results of the present study revealed a clear predominance of chloride (Cl^-) and sodium (Na^+) ions in both soil samples, confirming chloride-type salinity.

As shown in Table 6, the total soluble salt content was higher in the first sample (0.726%) compared to the second sample (0.416%), indicating a stronger salinization process in soils collected near cut *Rosa canina L.* plants.

Soil degradation indicators

Table 6. In terms of ionic distribution, chloride and sulfate ions were the dominant anions, while sodium and calcium were the main cations. The presence of elevated sodium levels suggests potential soil structural degradation and reduced nutrient availability for plants.

The Na/Cl ratio ranged from 0.98 to 1.1, confirming chloride-dominated salinity conditions. Additionally, toxic salt content was higher in the first sample (0.47%) compared to the second sample (0.21%), indicating more severe salinity stress.

The overall ionic balance (Table 7) shows a higher total ion sum in the first sample, reflecting greater salinity load and reduced soil quality.

Table 6. Ionic balance and salinity indices of soils.

Sample No.	Sampling location	Anion sum (meq/L)	Cation sum (meq/L)	Na/Cl ratio	Toxic salts (%)	Salinity classification
1	Soil near cut *Rosa canina L.* plants	10.729	10.484	0.98	0.47	Chloride-type, strongly saline
2	Soil near mature *Rosa canina L.* plants	6.151	5.955	1.10	0.21	Chloride-type, moderately saline

The composition of specific salts (Table 8) further confirmed that sodium chloride (NaCl) was the dominant salt type, followed by sulfate and carbonate forms. This salt structure is typical for arid irrigated soils affected by evaporation-driven salinization.

Table 7. Ionic composition of soil water extracts (1:5 suspension).

Sample No.	Sampling location	ECe (dS/m)	Total dissolved salts (%)	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Total ions (%)
1	Soil near cut *Rosa canina L.* plants	8.12	0.726	0.024	0.189	0.240	0.054	0.030	0.120	0.004	0.649
2	Soil near mature *Rosa canina L.* plants	5.20	0.416	0.031	0.063	0.186	0.050	0.016	0.046	0.007	0.383

Table 8. Composition of soil salts (%).

Sample No.	Sampling location	$Ca(HCO_3)_2$	$CaSO_4$	$MgSO_4$	Na_2SO_4	NaCl	$MgCl_2$	Non-toxic salts (%)	Toxic salts (%)	Total salts (%)
1	Soil near cut *Rosa canina L.* plants	0.016	0.170	0.149	-0.001	0.312	-	0.186	0.460	0.646
2	Soil near mature *Rosa canina L.* plants	0.020	0.153	0.077	0.028	0.104	-			

Discussion

The results of this study clearly demonstrate that soils in the Bukhara region are affected by a combination of salinity stress, alkaline reaction, and nutrient imbalance, which collectively drive progressive soil degradation processes in arid environments. The observed electrical conductivity values (5.20–8.12 dS/m) indicate moderate to very high salinity levels, which are known to create osmotic stress conditions that limit water uptake and reduce overall soil biological activity.

The dominance of sodium (Na^+) and chloride (Cl^-) ions confirms chloride-type salinization as the primary form of soil degradation in the studied area. This type of salinity is particularly harmful because sodium ions replace essential cations such as calcium and potassium on soil exchange sites, leading to deterioration of soil structure, reduced aggregation, and decreased permeability. Similar mechanisms have been widely reported in arid ecosystems, where sodium-induced dispersion of soil particles contributes to long-term physical degradation.

Slightly alkaline soil conditions (pH 7.6) further exacerbate nutrient availability constraints. Under such conditions, phosphorus becomes chemically immobilized through precipitation reactions with calcium compounds, resulting in reduced plant-available phosphorus despite moderate total phosphorus content. This explains the strong discrepancy between total and available phosphorus observed in this study.

Nitrogen dynamics showed an unusual pattern characterized by low total nitrogen but relatively high nitrate nitrogen levels. This suggests rapid mineralization processes typical of arid soils with limited organic matter inputs. However, such conditions are unstable, as nitrate forms are highly mobile and prone to leaching or denitrification losses, especially under fluctuating moisture conditions.

Potassium deficiency observed in both sampling sites is likely linked to competitive interactions with sodium ions. High sodium concentrations inhibit potassium uptake due to similar ionic properties, resulting in reduced potassium availability for plant metabolic processes. This ionic competition is a well-documented mechanism of salinity-induced nutrient imbalance in agricultural soils.

Despite moderate organic matter content, the overall soil fertility remains low due to the combined effects of salinity and nutrient imbalance. Organic matter alone is insufficient to maintain soil productivity under such stress conditions, particularly in the absence of active microbial processes that regulate nutrient cycling.

From a broader ecological perspective, the results indicate that soil degradation in the studied area is driven not only by salinity accumulation but also by complex ionic interactions that disrupt both physical and chemical soil properties. These findings are consistent with previous studies in arid and semi-arid regions, where salinity has been identified as a key driver of land degradation and reduced ecosystem resilience.

Importantly, the study highlights that soil degradation in arid environments should be interpreted as an integrated process involving salinity stress, ionic toxicity, and nutrient imbalance rather than a single-factor phenomenon. Therefore, effective soil management strategies should address both salinity reduction and nutrient restoration simultaneously.

The results also suggest that improving soil conditions in such environments requires integrated approaches, including enhancement of soil structure, regulation of ion balance, and restoration of nutrient cycling processes. In this context, biological and organic amendments may play a supportive role in improving soil resilience under salinity stress conditions. [15]

Conclusion

This study provides an integrated assessment of ionic composition, salinity status, and nutrient dynamics in arid soils of the Bukhara region, Uzbekistan. The results demonstrate that the investigated soils are affected by moderate to very high salinity levels, predominantly of chloride type, with electrical conductivity ranging from 5.20 to 8.12 dS/m and slightly alkaline reaction (pH 7.6). These conditions create a chemically unfavorable environment for sustainable soil functioning.

The dominance of sodium (Na^+) and chloride (Cl^-) ions confirms the presence of chloride-type salinization, which contributes to soil structural degradation, reduced permeability, and disruption of nutrient exchange processes. In addition, nutrient analysis revealed a pronounced imbalance characterized by low total nitrogen and potassium contents and critically low available phosphorus, despite moderate organic matter levels.

The study further highlights that nutrient availability is strongly constrained by ionic interactions under saline and alkaline conditions. In particular, sodium-induced competition with potassium and phosphorus fixation under alkaline conditions were identified as key mechanisms driving soil fertility decline.

Overall, the findings indicate that soil degradation in the studied area is a multi-factorial process driven by salinity stress, ionic toxicity, and nutrient imbalance. These interacting factors significantly reduce soil quality and limit the sustainability of land use in arid environments.

From a management perspective, the results emphasize the need for integrated soil improvement strategies, including salinity control, restoration of nutrient balance, and enhancement of soil biological activity. In this context, combined use of organic amendments, biofertilizers, and balanced mineral fertilization may contribute to improving soil resilience and mitigating the adverse effects of salinity.

This study contributes to a better understanding of soil degradation mechanisms in arid ecosystems and provides a scientific basis for developing sustainable soil management practices in Central Asian dryland regions.

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