Soil Salinization Characteristics in the Hongsibu Yellow River Pumping Irrigation Area, Ningxia: Postprint

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Abstract

To investigate the main influencing factors of soil salinization in the Hongsibu Pumped Yellow River Irrigation Area, correlation analysis and principal component analysis were employed to study the salinization characteristics of the 0~100 cm soil profile. The results indicated: (1) The soil in the study area was generally strongly alkaline, with pH values in the lower 20~100 cm soil layer being significantly higher than those in the upper 0~20 cm soil layer ($P<0.05$), and increasing with soil depth. Total soil salt content also increased with soil depth, exhibiting a bottom-accumulation profile characteristic of high bottom and low surface layers. The differences in total salt content among soil layers were not significant ($P<0.05$). The pH values of all soil layers showed weak variability and were relatively uniformly distributed spatially. Total soil salt content showed moderate variability in the upper 0~20 cm layer and strong variability in the lower 20~100 cm layer, with spatial distribution differences occurring with depth changes. (2) The main cations in the study area were Na^++K^+, with significant differences among cation contents ($P<0.05$). The main anion was $SO_4{}^{2-}$, which showed significant differences compared to other anion contents ($P<0.05$). The ion content order was $SO_4{}^{2-}$ > Na^++K^+ > Ca^{2+} > Mg^{2+} > $HCO_3{}^-$ > Cl^- > $CO_3{}^{2-}$. Ion concentrations also increased with soil depth, consistent with the changes in total salt and pH values. (3) Through correlation analysis and principal component analysis, it was found that the main factors affecting total salt in the irrigation area were $SO_4{}^{2-}$, Cl^-, Na^++K^+, and Mg^{2+}, while the main factors affecting pH were $CO_3{}^{2-}$ and $HCO_3{}^-$. The main salt types were sulfates and chlorides, but there were significant differences in salt types at different profile depths. The upper layer mainly contained chloride salts, while the lower layer contained a combination of sulfate and chloride salts. The research results identified the dominant factors influencing soil salt

characteristics in the Hongsibu Pumped Yellow River Irrigation Area, providing a theoretical basis for saline-alkali land management in the study area.

Full Text

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Abstract

To explore the main influencing factors of soil salinization in the Hongsipu Yellow River Irrigation Area, correlation analysis and principal component analysis were employed to investigate the salinization characteristics of the 0–100 cm soil profile. The results demonstrated: (1) The overall soil in the study area is strongly alkaline, with the pH of the lower layer (20–100 cm) significantly higher than that of the upper layer (0–20 cm) ($P<0.05$), increasing progressively with soil depth. The total salt content also increases with depth, exhibiting a bottom-accumulation profile pattern of high subsurface and low surface values. Inter-layer differences in total salt content were not statistically significant ($P<0.05$). The pH values of all layers showed weak variability with relatively uniform spatial distribution. Total salt content displayed moderate variability in the upper 0–20 cm layer and strong variability in the lower 20–100 cm layer, with spatial distribution differences emerging as depth increased. (2) The dominant cation is Na^++K^+, with significant concentration differences among cations ($P<0.05$). The dominant anion is SO_4^{2-}, showing significant differences compared to other anions ($P<0.05$). Ion concentrations increase with soil depth, consistent with total salt and pH changes. (3) Correlation and principal component analyses revealed that the main factors affecting total salt are SO_4^{2-}, Cl^-, Na^++K^+, and Mg^{2+}, while the primary factors influencing pH differ. The main salt types are sulfates and chlorides, but significant differences exist across depths: the upper layer is dominated by chlorides, whereas the lower layer contains a sulfate-chloride composite. These findings identify the dominant factors controlling soil salinity characteristics in the Hongsipu Yellow River Irrigation Area, providing a theoretical basis for saline-alkali land management.

Keywords: saline-alkali land; salinization characteristics; correlation analysis; principal component analysis; Hongsipu Yellow River Irrigation Area; Ningxia

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1 Introduction

Soil salinization is a form of soil degradation resulting from the gradual accumulation of salts through natural processes or improper irrigation practices. It occurs widely in inland arid regions and has become a global environmental issue. Excess soluble salt ions in soil adversely affect plant growth and development through osmotic stress and ion toxicity, thereby undermining agricultural productivity. Regional salinization research provides essential decision-making support for rational land development, offering significant benefits for preventing and controlling soil salinization, improving land use efficiency, maintaining ecological security, and achieving sustainable development.

Currently, scholars worldwide have extensively investigated soil salinity characteristics using correlation analysis and principal component analysis. Numerous studies have reported on relationships among various salt ions and physicochemical properties. Analyzing correlations between soil pH, salinity, and ions forms the basis for understanding soil salinity composition patterns, effectively revealing salt distribution and states, reflecting ion homology, inferring salt sources, and indicating salt migration trends. Principal component analysis reduces dimensionality while objectively describing sample characteristics, finding wide application in soil salinity studies.

Liu *et al.* classified salinization degrees and analyzed influencing factors in the Chanann Irrigation Area, identifying alkaline soils and ${SO_4}^{2-}$ as primary salinization factors, with total salt positively correlating with all ions. Principal component analysis identified Na^+ as the dominant factor. Research in the Sino-Singapore Tianjin Eco-City found Cl^- and ${SO_4}^{2-}$ as main controls on soluble salt content, informing remediation strategies. Guo *et al.* analyzed aeolian sandy soils in the Ebinur Lake basin, determining chloride-sulfate and sulfate types as dominant, classifying the area as saline soil.

The Hongsipu Irrigation Area features red soil parent material, primarily in severely eroded hilly regions, appearing reddish-brown with high clay content, high salt concentrations, and thin effective soil layers. Irrigation dissolves subsurface salts, which migrate to the tillage layer through evaporation, causing salinization. Incomplete drainage infrastructure, high groundwater tables with dissolved salts, and subsurface impermeable layers exacerbate secondary salinization, now covering substantial portions of the irrigation area.

Previous studies have assessed Hongsipu's saline-alkali status. Yu *et al.* comprehensively analyzed potential secondary salinization risks, latency periods, and treatment difficulties. Fang *et al.* evaluated salinization using WET sensors, finding groundwater depth and Total Dissolved Solids (TDS) decreasing from north to south, with shallower groundwater corresponding to more severe salinization. Since saline soil types and improvement methods vary regionally, characterizing salinization patterns is crucial for providing scientific management guidance.

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2 Data and Methods

2.1 Soil Sampling

Based on the distribution of the Hongsipu Yellow River Irrigation Area, sampling points were systematically arranged across agricultural land. Points located in construction zones or water bodies were relocated to adjacent farmland. Seventy-two sampling points were established at 2 km intervals. At each point, soil cores were collected at 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm depths. Five subsamples per point were mixed using the diagonal method. Layer-specific ion contents were averaged for analysis. Sampling occurred in March–April 2021 before spring irrigation.

2.2 Measurement Methods

Soil samples were air-dried, ground, and sieved. All samples were prepared as 1:5 soil-water extracts. pH and electrical conductivity were measured using a Mettler portable multi-parameter tester, with total salt content calculated subsequently. Soluble ion measurements followed *Agrochemical Analysis of Soil*. $CO_3{}^{2-}$ and $HCO_3{}^{-}$ were determined by standard H_2SO_4 titration, Cl^- by $AgNO_3$ titration, Ca^{2+} and Mg^{2+} by complexometric titration, and Na^++K^+ by flame photometry.

2.3 Data Analysis

Statistical analysis of total salt, pH, and soluble ions was performed using Excel. SPSS 25.0 conducted variance, correlation, and principal component analyses. Origin 2022 generated profile diagrams, while ArcGIS mapped the study area, sampling locations, and inverse distance weighting interpolations.

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3 Results

3.1 Soil Profile Characteristics

Total salt content and pH are critical indicators of salinization and alkalization. Statistical analysis of salinization parameters across soil layers (Table 1) revealed overall pH ranges of 8.95–9.08, indicating strongly alkaline soils. Lower layer (20–100 cm) pH significantly exceeded upper layer (0–20 cm) values ($P<0.05$), increasing consistently with depth. Total salt content also increased with depth, showing a bottom-accumulation pattern (Figure 2). Inter-layer total salt differences were non-significant ($P<0.05$). According to national salinization classification standards, the study area exhibits low overall salinization, with slightly and moderately saline soils distributed sporadically.

As shown in Figure 3, Na^{+}+K^{+} and SO_4^{2-} concentrations significantly surpassed other ions across depths ($P<0.05$), except at 80–100 cm where differences were non-significant. Na^{+}+K^{+} dominated cations, comprising >50% of total cations and significantly exceeding other cations ($P<0.05$). Ca^{2+} concentrations exceeded Mg^{2+} in all layers. Among anions, SO_4^{2-} showed highest concentrations, significantly greater than others ($P<0.05$), followed by Cl^{-}. HCO_3^{-} concentrations were lowest, with CO_3^{2-} undetected in some samples. The dominant salt type is chloride-sulfate.

The coefficient of variation (Cv) reflects data dispersion: Cv$ 10 100^{2+}$ and Mg^{2+}, possibly due to $CaCO_3$ and $MgCO_3$ precipitation in deep impermeable layers.

3.2 Correlation Analysis

Correlation analysis reveals ion existence forms and accumulation characteristics. Results (Figure 5) showed:

- **0–10 cm:** Total salt correlated extremely significantly with Na^{+}+K^{+} (r=0.834, $P<0.001$) and Cl^{-} (r=0.826, $P<0.001$)
- **10–20 cm:** Similar extremely significant correlations maintained
- **20–40 cm:** Total salt correlated extremely significantly with Na^{+}+K^{+}, Cl^{-}, and SO_4^{2-} (r=0.831, 0.816, 0.815; $P<0.001$)
- **40–60 cm:** Extremely significant positive correlations with Na^{+}+K^{+}, Cl^{-}, SO_4^{2-}, and negative correlations with Ca^{2+} and Mg^{2+} (r=-0.481, -0.427; $P<0.001$)
- **60–80 cm:** Extremely significant positive correlations with Na^{+}+K^{+}, Cl^{-}, SO_4^{2-} (r=0.847, 0.831, 0.835; $P<0.001$) and negative correlations with Ca^{2+} and Mg^{2+}
- **80–100 cm:** Extremely significant positive correlations with Na^{+}+K^{+}, Cl^{-}, SO_4^{2-} (r=0.862, 0.841, 0.859; $P<0.001$); correlations with other ions weakened

Overall, Na^{+}+K^{+} and Cl^{-} primarily controlled total salt, while pH was mainly affected by CO_3^{2-} and HCO_3^{-}. Ca^{2+} and Mg^{2+} decreased pH. Correlations between SO_4^{2-} and total salt/pH strengthened with depth, while Cl^{-} correlations weakened but remained strongest. Upper layer total salt comprised mainly Na^{+}+K^{+} and Cl^{-} chlorides, while lower layer total salt consisted of sulfate-chloride composites.

3.3 Principal Component Analysis

Principal component analysis requires inter-variable correlation, verified by KMO and Bartlett's Test (KMO=0.754, $P<0.001$), confirming suitability.

Two principal components were extracted from layer-averaged total salt, pH, and salt ion data (Table 2). Principal component one (eigenvalue=4.96) and component two (eigenvalue=3.01) explained 49.58% and 30.06% of variance respectively, with a cumulative contribution of 69.94%. The first component, containing most information, featured high positive loads from $Na^{+}+K^{+}$ (0.934), Cl^{-} (0.920), SO_4^{2-} (0.918), and Mg^{2+} (0.902)—the main total salt influencers. These ions showed extremely significant positive correlations with total salt and among themselves, representing soil salinization status. The second component featured high pH loading, reflecting alkalinity degree. Thus, $Na^{+}+K^{+}$, Cl^{-}, SO_4^{2-}, and Mg^{2+} are the main characteristic factors affecting regional soil salinity-alkalinity.

Component score matrices were calculated (Table 3):

$$\mathbf{F}_1 = -0.170(pH) + 0.434(TS) - 0.020(CO_3^{2-}) + 0.374(Cl^{-}) + 0.420(SO_4^{2-}) + 0.393(Na^{+}+K^{+}) + 0.376(Ca^{2+}) + 0.406(Mg^{2+})$$

$$\mathbf{F}_2 = 0.527(pH) + 0.216(TS) + 0.461(CO_3^{2-}) - 0.335(HCO_3^{-}) + 0.370(Cl^{-}) - 0.205(SO_4^{2-}) + 0.295(Na^{+}+K^{+}) - 0.278(Ca^{2+}) - 0.085(Mg^{2+})$$

Coefficient magnitudes indicate indicator weights in comprehensive scores. The first component weights $Na^{+}+K^{+}$, Cl^{-}, SO_4^{2-}, and Mg^{2+} most heavily, followed by total salt. The second component weights pH, CO_3^{2-}, and HCO_3^{-} most heavily, confirming these as primary salinization factors.

Validation using inverse distance weighting interpolation of pH, total salt, and component scores showed spatial distributions of component one and two scores consistent with pH and total salt patterns (Figure 6), verifying that component one represents total salt content and component two represents pH. This confirms that principal component analysis correctly evaluates soil salinization in the Hongsipu Yellow River Irrigation Area.

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4 Discussion

Analyzing soil total salt, pH, and salt ion characteristics across layers reveals salinization degrees and ion compositions, providing theoretical guidance for prevention and remediation.

Profile characteristics: pH, total salt, and ion contents increase with depth. First, Hongsipu's arid climate and limited flood irrigation volumes prevent effective leaching. Second, high-salt red soil parent material and impermeable layers at 80–100 cm concentrate salts in deep layers. Third, corn cultivation, known to inhibit surface salinity, promotes salt accumulation in lower layers through seasonal cycling, creating bottom-accumulation profiles.

Salt composition: pH positively correlates with CO_3^{2-} and HCO_3^-, consistent with findings that these ions determine pH values. Salinization type depends on SO_4^{2-} and Cl^- concentrations, aligning with research showing these ions determine depth-specific salinization patterns. Wang *et al.* demonstrated inverse relationships between sulfate and chloride contents. Zhang *et al.* found SO_4^{2-}-total salt correlations weaken with depth but remain strong. In Hongsipu, chloride migration dominates, while sulfate moves slower—consistent with Qi *et al.*'s findings that Cl^- mobility exceeds SO_4^{2-}.

The Hongsipu Irrigation Area, developed for >20 years with five salinization surveys, reached 5,980 hm^2 of salinized land by 2020, increasing annually. In arid regions, improper irrigation induces salinization. "Salt comes with water, salt leaves with water"—water management is key. Implementing efficient irrigation-drainage systems to control water volumes and prevent salt accumulation is the primary remediation task. Soil salinity is also influenced by climate, topography, land use, and anthropogenic factors, creating complex patterns. This study focused on spring agricultural soils without examining seasonal dynamics—an important future research direction.

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5 Conclusions

1. Soils are strongly alkaline with pH increasing with depth, showing weak variability across layers and stabilizing in deep layers. Total salt content is relatively low but increases with depth, exhibiting clear bottom-accumulation. Total salt shows moderate variability at 0–20 cm and strong variability at 20–100 cm.

2. Na^++K^+ dominates cations with significant inter-cation differences ($P<0.05$). The anion sequence is $SO_4^{2-} > Cl^- > HCO_3^-$, with concentrations significantly exceeding other anions ($P<0.05$). Ion concentrations increase with depth, consistent with total salt and pH, showing bottom-accumulation.

3. Correlation and principal component analyses identify SO_4^{2-}, Cl^-, Na^++K^+, and Mg^{2+} as main total salt factors, while CO_3^{2-} and HCO_3^- primarily affect pH. Salt types differ significantly by depth: upper layers are chloride-dominated, lower layers contain sulfate-chloride composites.

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Note: Figure translations are in progress. See original paper for figures.