RESEARCH ARTICLE

Impacts of rainfall and irrigation on the seasonal dynamics of salt content in saline-alkali soil in Cangzhou, Hebei, China

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Coastal saline-alkali soils face severe salt accumulation due to high groundwater and intense evaporation, yet the seasonal dynamics under rainfall and irrigation remain unclear. This study investigated the seasonal migration of soil salinity and the regulatory mechanisms of rainfall and irrigation in saline-alkali area of Cangzhou, Hebei, China. A two-year field experiment from 2022 - 2024 was conducted with 12 monitoring plots across different salinization gradients. Soil samples were collected from 0 - 20, 20 - 40, and 40 - 60 cm depths across seasons, measuring electrical conductivity (EC), pH, total salt, and major ions of Cl^-, SO_4^{2-}, Na^+. Results revealed a typical pattern of spring salt return → summer desalination → autumn/winter salt accumulation. Surface salinity at 0 - 20 cm depth peaked at 7.30 g/kg in autumn and dropped to 1.85 g/kg in summer. Rainfall reduced surface salinity to 2.23 g/kg and lowered pH throughout the 0 - 60 cm profile, while irrigation decreased surface salt but caused deep-layer at 40 - 60 cm accumulation. Cl^-, SO_4^{2-}, and Na^+ followed the same seasonal trends. Canonical correlation analysis identified Cl^- and Na^+ as dominant drivers with their influence weakening as depth increased. The study concluded that summer rainfall leaching was the primary desalination driver, and irrigation must account for hydrological patterns to avoid secondary salinization. These findings supported sustainable water-salt management combining salt-tolerant crops and water-saving irrigation.

Keywords: saline-alkali soil; seasonal changes; rainfall; irrigation regulation; salt dynamics.

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Introduction

In coastal saline-alkali areas such as Cangzhou, Hebei, China, due to high groundwater levels, intense evaporation, and limited freshwater resources, soil salinization is serious. The annual precipitation in this region is less than 600 mm with 70% of the precipitation concentrated from June to August, forming a "spring drought - summer flood" pattern. This pattern does not match the water demand of winter wheat, leading to excessive extraction of groundwater and triggering soil subsidence and other ecological problems. Current research indicates that rainfall leaching can reduce surface salt content and soil acidity, while saline water irrigation can temporarily alleviate the water stress on crops, but there is a risk of deep salt accumulation [1, 2].

Existing water-salt control strategies include underground drainage, covering, micro-sprinkler systems, and alternating freshwater and saline water irrigation [3]. In response to the soil health degradation caused by long-term saline water irrigation, many scholars have conducted extensive research on various irrigation strategies and improvement measures. Yadav *et al*. proposed a dynamic assessment method of soil microorganisms based on different saltwater treatment strategies. Through neutralization improvement with gypsum and dilute sulfuric acid, the improvement effect of diluting sulfuric acid depended on the content of original calcium carbonate in the soil, and its long-term stability was limited [4]. Gao *et al*. proposed a safety scheme for irrigating winter wheat with salt water under the underground drainage system to address the insufficient fresh water in the saline-alkali land for two consecutive years and found that saltwater irrigation combined with underground drainage could achieve safe utilization of saltwater [5]. Soni *et al*. designed a scheme for optimizing the planting system by combining irrigation with mulching and tillage in response to the limitations of rain-fed sorghum production in saline soil. The effects of irrigation intensity, tillage methods and coverage on yield showed that irrigation combined with reduced tillage could reduce the negative impact of soil salinity on crops [6]. Chu *et al*. explored the application of the three-stage water and salt regulation technology of micro-sprinkler irrigation in the reclamation of coastal saline soil. By adjusting the soil matrix potential of 20 cm, combined with tall fescue planting experiments, three-level micro-sprinkler irrigation eliminated the accumulated soil salt, promoted the transformation of high-saline soil to medium-saline soil, and improved growth indicators such as plant height and tillers [7]. Other studies focused on the impact of factors such as irrigation intensity, freeze-thaw cycles, alternating saltwater irrigation, and shallow groundwater levels on soil salinity dynamics and crop growth. Wendemeneh *et al*. revealed the association between irrigation intensity and soil salinization on the spatiotemporal variation of soil salinity. The results showed that the electrical conductivity (EC) and the percentage of exchangeable sodium in irrigated fields were significantly higher than that in rain-fed fields. It was recommended to alleviate the risk of alkalization through deep ploughing, breeding salt-tolerant crops, and drainage management [8]. Jia *et al*. investigated the influence of precipitation patterns on the migration of soil water and salt based on freeze-thaw cycle and found that the infiltration of melting snow led to the surface salt dropping to 60.65% of the initial value, triggering mud rolling and salt weathering, while rainfall formed crusting and bottom salt zones, providing mechanism support for soil protection [9]. Soothar *et al*. proposed an alternating irrigation strategy of salt and fresh water and reported that the combination of salt water during the jointing stage and fresh water during the flowering stage could increase the yield of winter wheat by 32%, while the salt content was balanced inter-year, providing an optimization scheme for the safe utilization of shallow saltwater resources [10]. Neha *et al*. used rice husks to fill ditches to reduce soil salinity by 60% and increase the yield of pearl millet by 23.54%, confirming the feasibility of this technology in treating small-scale saline-alkali land [11]. Kiremit *et al*. artificially explored the influence of shallow saline groundwater on the critical growth stages of crops by optimizing the germination parameters of wheat seeds under shallow saline water conditions through the response surface model, providing quantitative standards for crop breeding in saline areas [12].

However, most studies only focus on a single driving factor or interannual salt balance. High-frequency monitoring of rainfall intensity and irrigation frequency of dynamic salinity at different soil depths is lacking, and quantitative salinity thresholds for key crop growth stages have not yet been determined [13, 14]. This research aimed to reveal the interaction mechanism between rainfall leaching and saline-alkali irrigation on seasonal salt content dynamics and quantify the salt response thresholds under different hydrological years. The study combined field experiments and indoor simulations, setting up 12 long-term monitoring points in different saline-alkali gradient areas in Cangzhou, Hebei, China. Multiple-source data including meteorology, groundwater, and soil salinity were collected to analyze the spatiotemporal migration of salt content. This research explored the interaction mechanism between rainfall leaching and saline irrigation on the seasonal migration of soil salinity and quantified the response threshold of soil salinity flux under different hydrological year types. The results of this research provided support for irrigation plan optimization, salt-tolerant crop selection, and water-saving technologies in coastal saline-alkali areas.

Materials and methods

Overview of the research area

This research was conducted in saline-alkali land in the eastern part of Cangzhou, Hebei, China (38°00′ - 38°30′ N, 117°10′ - 117°50′ E), a typical coastal saline-alkali region in the Bohai Rim low plain. The site was approximately 30 km from Bohai Bay with an elevation of 2 - 5 m. Groundwater depth was 1 - 2 m in dry season and less than 0.5 m in rainy season. Both soil salinization and high groundwater mineralization were prevalent. The region had a warm temperate, semi-humid continental monsoon climate with a frost-free period of 200 - 210 days. During the study period of 2022 - 2024, the average annual temperature was 14.5℃. The average annual precipitation was 544.1 mm, of which 70% was concentrated from June to September, presenting the precipitation characteristics of "spring drought and summer flood". The aquifer thickness was 5 – 10 m, while the permeability coefficient was 0.5 -1.2 m/d, and salt content readily moved upward *via* capillary action. Saline-alkali soil in Cangzhou accounted for approximately 30% of the total cultivated land area, mainly concentrated in eastern coastal counties and cities, as well as low-lying areas inland. The soil types were mainly fluvo-aquic soil and saline soil. Surface salt content fluctuated significantly by season from 0.2 - 1.5%, and the salt composition was dominated by Na^+ and Cl^-. Local agriculture was based mainly on winter wheat-maize rotation, and irrigation water sources were mainly groundwater. Due to scarce freshwater resources, some areas had long relied on brackish water containing 1 – 3 g/L mineralization for irrigation, resulting in prominent secondary salinization. The traditional flood irrigation model with the average annual irrigation volume of 300 - 400 mm combined with natural rainfall led to complex seasonal salt dynamics in the “leaching-evaporation” cycle, which was the core bottleneck restricting sustainable regional agricultural development.

Experimental plot layout and gradient design

Sample plots were chosen following a gradient difference principle of salinization and divided into three categories based on surface soil EC including mild salinization (< 4 dS/m), moderate salinization (4 – 8 dS/m), and severe salinization (> 8 dS/m). The plots were further divided into agricultural cultivated land and non-cultivated land according to land use type. Agricultural cultivated land was mainly under winter wheat-maize rotation, while non-cultivated land was mainly natural wasteland. To compare natural processes with human intervention, two groups of control plots were established as natural rainfall area and irrigation area with mineralization degree of 1 – 3 g/L. All sample plots were 5 × 5 m^2. Isolation trenches 50 cm deep were excavated at the boundaries and filled with impermeable layers to block lateral salt migration. The study period covered three complete hydrological years from 2022 to 2024, ensuring that data included climate fluctuations in wet, normal, and dry years.

Multi-source data collection and monitoring plan

Meteorological data including daily rainfall and temperature were continuously obtained by using HOBO U30 automatic weather stations (Onset Computer Corporation, Bourne, MA, USA). The stations were set up in the open area at the center of the sample plot. Groundwater was monitored by using Solinst Levelogger Edge pressure-type water level gauge (Solinst Canada Ltd., Georgetown, ON, Canada) to record burial depth changes in real time. Groundwater samples were collected simultaneously each month. Salinity and pH were determined by using Hach HQ40D multi-parameter water quality analyzer (Hach Company, Loveland, CO, USA), and the main salt ion composition was analyzed by using Dionex ICS-600 ion chromatography (Thermo Fisher Scientific, Sunnyvale, CA, USA). The irrigation event was recorded by using SXS-15E agricultural water meter (Ningbo Water Meter Co., Ltd., Ningbo, Zhejiang, China) to accurately measure irrigation volume. Meanwhile, irrigation time, water source type, and irrigation method were manually recorded to ensure uniformity. Soil samples were collected in three layers of 0 - 20 cm, 20 - 40 cm, and 40 - 60 cm in March, June, September, and December each year. During the rainy season of July to September, the sampling frequency was increased to once a month to track the salt leaching process after heavy rainfall. Sampling was conducted using the diagonal five-point mixing method. Five sampling points were selected from each plot. After removing the plant roots and crushed stones, the samples were passed through a 2 mm nylon sieve and divided into fresh samples and air-dried samples for EC determination [15]. Artificial rainfall simulation experiments were conducted as control tests using custom-made stainless steel soil columns with the height of 1 m and the diameter of 30 cm filled with the original saline-alkali soil to reproduce the natural soil profile structure. Two rainfall scenarios were tested as 20 mm/h for moderate rainfall intensity and 0 mm/h for no rainfall control. By collecting seepage water at different depths, the law of salt transport with water was analyzed to quantify the influence of rainfall leaching on the vertical distribution of soil salt. Two irrigation treatments were applied including traditional flooding irrigation with an annual irrigation volume of 400 mm, implemented twice during the green-up period and the jointing period of winter wheat and rain culture without irrigation control. The irrigation time was strictly synchronized with the local agricultural calendar. Groundwater with a salinity of 2.5 g/L was used in the irrigation area. Soil and groundwater samples were collected respectively before and after irrigation to analyze the balance of salt input and output.

Electrical conductivity measurement

Soluble salt content in soil was quantified by EC measurement using a DDS-307A conductivity meter (Shanghai Leici Instrument Co., Ltd., Shanghai, China). Soil extraction solution was prepared at a 1:5 soil:water ratio, shaken for 30 min, allowed to settle. The supernatant was used for EC measurement. The value was then converted to total salt (TS) content (g/kg) according to a standard curve.

Total soluble salts determination

Soluble salt ion components were analyzed to determine the concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}. Sample was pretreated by leaching solution filtration using 0.45 μm microporous membrane and diluted with a detection limit of 0.01 mg/L. A relative standard deviation of less than 3% was adopted for repeated measurements.

Soil pH value measurement

Soil pH was measured by using a PHS-3E pH meter (Shanghai Leici Instrument Co., Ltd., Shanghai, China). The soil sample was mixed with water at soil:water ratio of 1:2.5. The mixture was shaken and left to stand for 30 minutes. The average of three parallel measurements was taken with an accuracy of ± 0.01.

Soil nitrate nitrogen and ammonium nitrogen determination

Soil nitrate nitrogen and ammonium nitrogen were extracted and filtered by using 1 mol/L KCL method. The supernatant was applied to SEAL AA3 continuous flow analyzer (SEAL Analytical GmbH, Norderstedt, Germany) for Soil nitrate nitrogen and ammonium nitrogen determination.

Statistical analysis

SPSS version 26.0 (IBM, Armonk, NY, USA) was employed for statistical analysis of this research. One-way analysis of variance (ANOVA) was

Table 1. Statistical results of monitoring data.

Soil layer depth (cm)	Sampling time	pH value	Total salt content (g/kg)	Standard deviation	Coefficient of variation
0 - 20	Spring	8.118	7.30	8.15	1.10
	Summer	8.023	1.85	2.47	1.29
	Autumn	8.145	2.52	1.81	0.68
	Winter	8.109	4.61	4.60	1.00
20 - 40	Spring	8.101	4.60	4.07	0.83
	Summer	8.097	1.47	1.82	1.27
	Autumn	8.186	2.38	1.09	0.44
	Winter	8.078	3.71	2.23	0.58
40 - 60	Spring	8.120	3.97	3.40	0.81
	Summer	8.117	1.10	0.74	0.70
	Autumn	8.214	2.42	1.43	0.57
	Winter	8.063	3.22	1.97	0.59

applied for different salinization gradients and irrigation treatments comparisons followed by Tukey HSD test. P value less than 0.05 was defined as statistically significant difference.

Results

The impact of rainfall and irrigation on saline-alkali soil

The statistical results of salinity in each soil depth layer demonstrated that the soil in the study area was generally alkaline with the pH value variation range of 8.023 - 8.214. There were small differences among different seasons. The total salt content of the soil showed significant seasonal fluctuations. Overall, the salt content showed the characteristics of spring > autumn > winter > summer. This dynamic change was mainly influenced by the combined effect of the source of salt and its migration and transformation process. The soil salinity in the plow layer 0 - 20 cm had a standard deviation of 1.81 - 8.15 g/kg and a coefficient of variation of 0.68 - 1.29, indicating strong variability. The 20 - 60 cm soil layer showed a standard deviation of 0.74 - 4.07 g/kg and a coefficient of variation of 0.44 - 1.27, mostly with moderate variability (Table 1). The results indicated that the salinity in the cultivated layer was more directly and strongly affected by human activities such as irrigation and farming.

Effects of rainfall and irrigation on soil pH

The changes in soil pH before and after irrigation and rainfall showed that both irrigation and rainfall significantly reduced the pH value of the surface soil (0 – 20 cm) with the reduction rates reaching 0.86% and 1.49%, respectively. However, there were differences in the effects of the two water input methods on deep soil. Although irrigation effectively reduced the alkalinity of the surface layer, it led to an increase in the pH value of the underlying soil (40 – 60 cm), which might cause the accumulation of salt downward (Figure 1a). A decrease in pH value was observed throughout the entire soil profile (0 – 60 cm), and the rainfall effect was more comprehensive (Figure 1b), which indicated that a single irrigation mainly acted on the surface layer, but it might be accompanied by the risk of deep salt accumulation. The leaching effect produced by continuous rainfall could promote the process more effectively.

Effects of rainfall and irrigation on total soil salinity

The changes in total soil salinity before and after irrigation and rainfall demonstrated that soil salinity exhibited significant surface aggregation

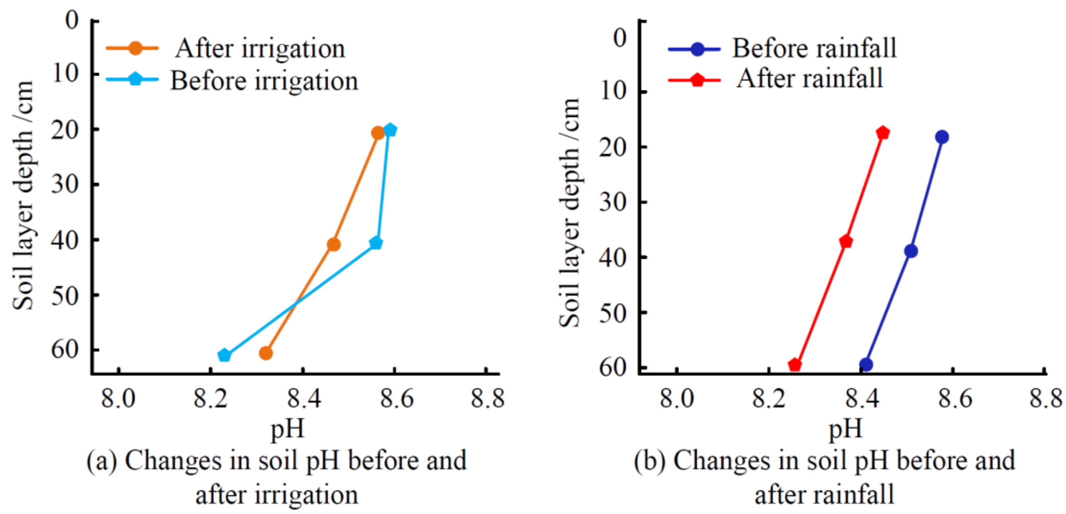

Figure 1. The changes of soil pH before and after irrigation or rainfall.

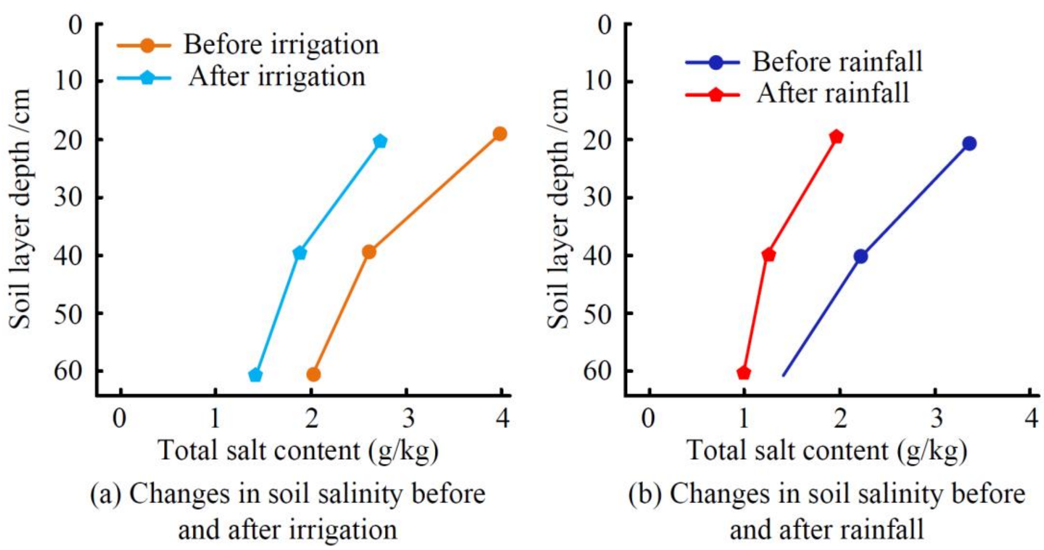

Figure 2. The variation of total soil salinity.

characteristics, reaching 4.10 g/kg before irrigation and 3.51 g/kg before rainfall, respectively. Irrigation and rainfall both caused salt leaching with surface salt levels dropping to 2.77 g/kg and 2.23 g/kg, respectively. The desalination rate of irrigation decreased in depth (Figure 2a). Rainfall still maintained a high desalination rate in the 40 – 60 cm soil layer, indicating a deeper leaching effect (Figure 2b). The overall desalination rate of rainfall was significantly higher than that of irrigation, which indicated that continuous rainfall had a more thorough leaching effect on salt, not only effectively reducing surface salt content, but also effectively affecting deep soil layers. However, single irrigation mainly affected shallow layers, and the desalination efficiency in deep layers was limited.

Canonical correlation analysis of salt driving factors in different soil layers

The two-dimensional canonical correlation analysis (CCA) ranking chart of salt content in different soil layers showed that Ca^{2+}, Mg^{2+}, K^{+},

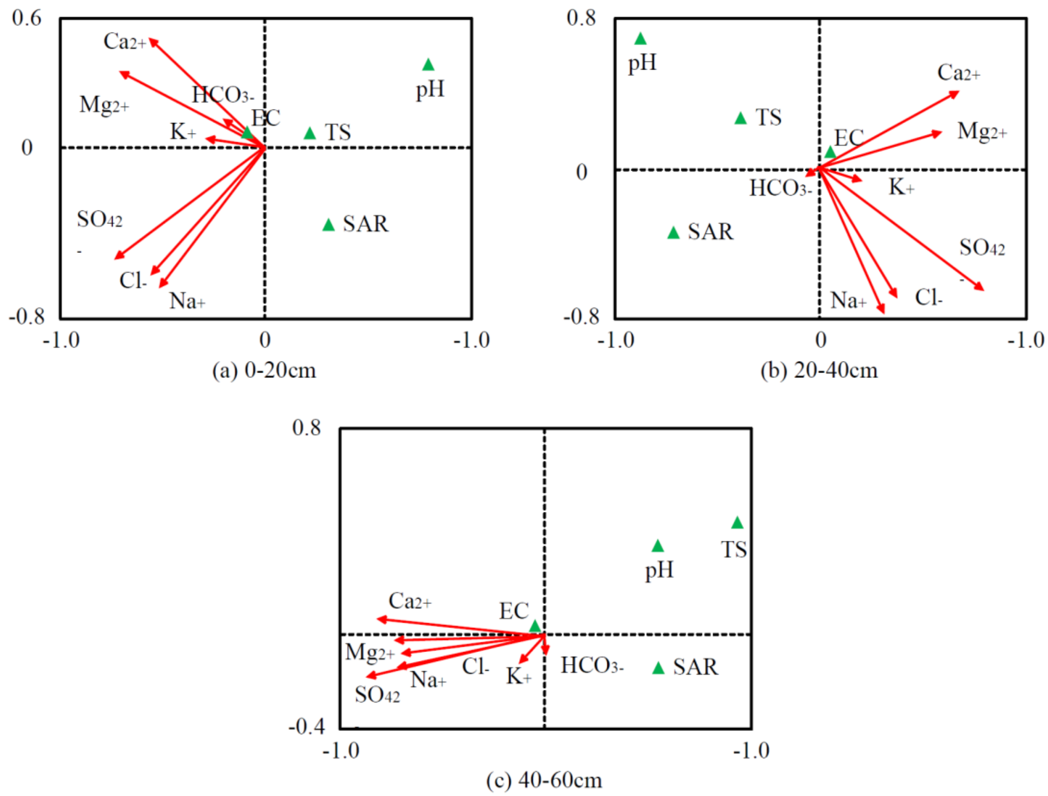

Figure 3. Two-dimensional CCA ranking map of salt in each soil layer.

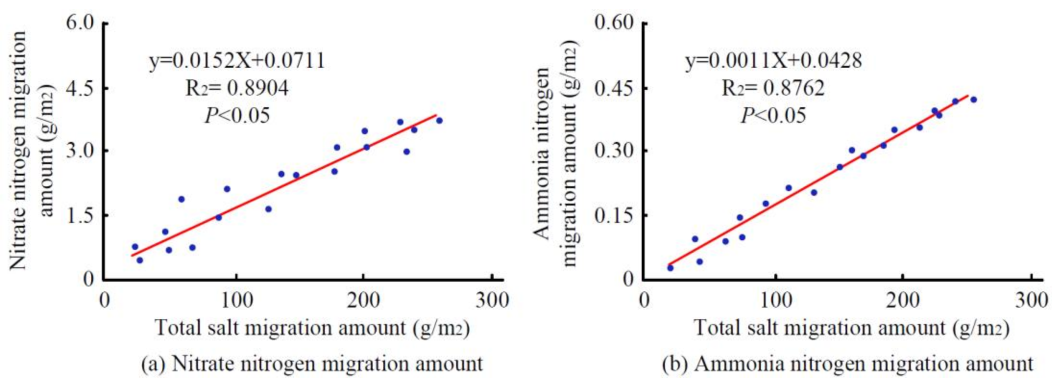

Figure 4. Coupling migration analysis of soil salinity and nutrients.

Na^+, Cl^-, SO_4^{2-}, and HCO_3^- were the main driving factors for salt changes. The influence of salt ions in the 0 – 20 cm soil layer was significantly stronger than that of pH, EC, TS, and sodium adsorption ratio (SAR) (Figure 3a). The driving effect of ions on salt content in the 20 – 40 cm soil layer was weakened, while the relative contribution of environmental factor was enhanced (Figure 3b). The influence of ions in the 40 – 60 cm soil layer was significantly reduced, and environmental factor was the key factor dominant in salt changes (Figure 3c). As soil depth increased, the direct driving effect of salt ions on salt dynamics gradually weakened, while the influence of environmental factors such as pH, EC, TS, and SAR continued to increase,

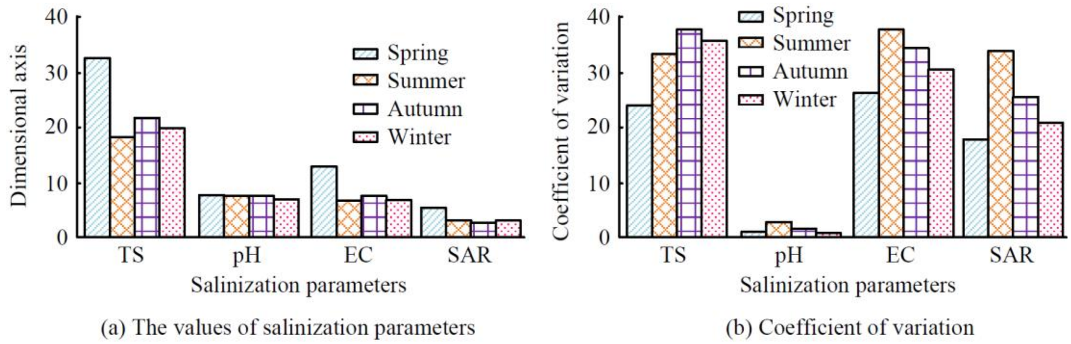

Figure 5. Seasonal variations of each indicator.

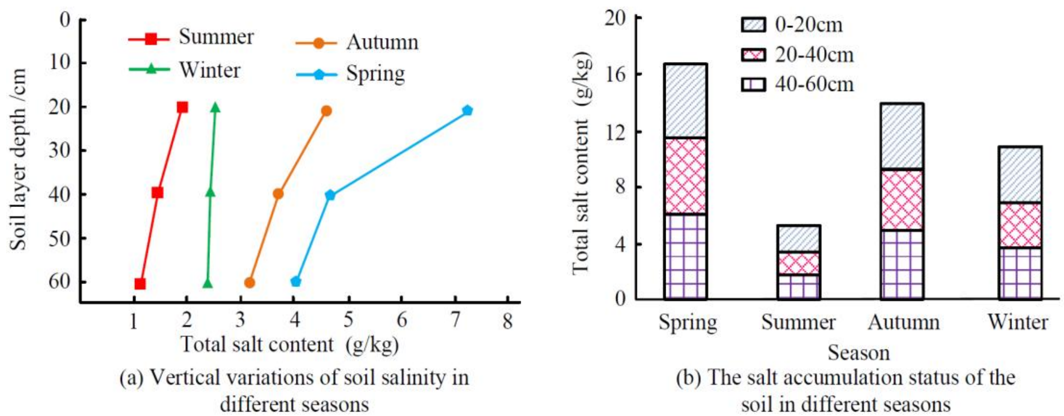

Figure 6. Analysis of seasonal variations in soil salinity.

playing a dominant role in deep soil (> 40 cm).

Coupled migration of soil salinity and nutrients

The coupled migration analysis of soil salinity and nutrients showed that the migration processes of nitrate nitrogen and ammonium nitrogen exhibited the same mobility characteristics, showing that they moved downward with rainfall or irrigation water and leached to the bottom layer. There were highly significant positive correlations between soil salinity and both nitrate nitrogen and ammonium nitrogen contents ($P < 0.05$) (Figure 4). The results indicated that, during the seasonal water and salt dynamic process caused by rainfall and irrigation, the soil salt level had a significant regulatory effect on the content distribution of nitrogen nutrients, revealing that the water input pattern affected the soil nutrient cycle by changing the salt migration path.

Analysis of seasonal variation patterns of salt in 2023

The pH value and SAR of the soil were the key diagnostic indicators for evaluating whether soil salinization had occurred and the degree of salinization. The seasonal variation of soil pH was weak with the average value ranging from 7.7 to 8.1. However, the seasonal difference was significant, and the coefficient of variation was only 2.0 to 4.3%. The SAR value ranged from 3.08 to 5.29, and the EC was from 7.16 to 13.04 mS/cm (Figure 5). The seasonal dynamics of these indicators suggested that the water-salt movement driven by rainfall and irrigation was a key process in regulating soil salinity and alkalinity. The salt content of each soil layer demonstrated that the mean soil salinity showed significant seasonal differentiation in its vertical distribution and salt accumulation pattern. In spring, autumn, and winter, it was manifested as

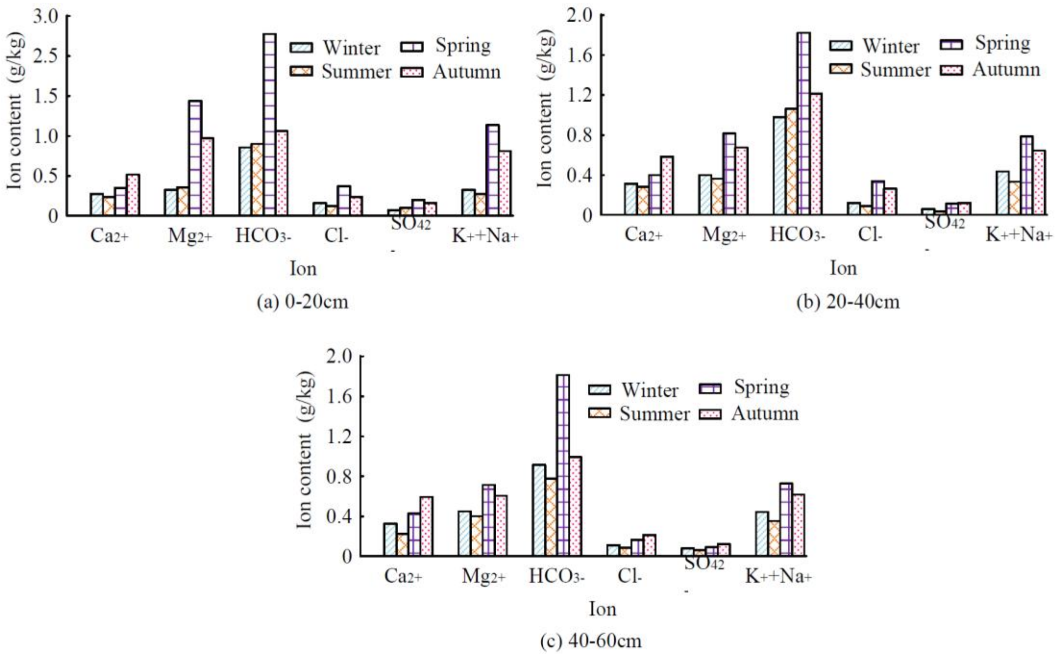

Figure 7. Soil salt ion contents and seasonal distribution characteristics.

salt accumulation, while in summer, it was the leaching process. The overall order of salt accumulation intensity was spring > autumn > winter > summer (Figure 6a). The vertical distribution of salt showed seasonal characteristics. In spring, it decreased with the deepening of the soil layer, and the salt suddenly decreased at 20 to 40 cm, presenting a typical surface accumulation type, which was mainly because the strong evaporation in autumn and the drought and less rainfall in winter and spring caused the salt to remain in the surface layer, and the soil freezing in winter further inhibited the downward movement. In summer, the salt content first decreased and then increased with depth and became a basal accumulation type, reflecting that the increase in precipitation promoted the migration of salt to deeper layers (Figure 6b). This rule confirmed the core regulatory role of rainfall and irrigation in the seasonal dynamics of salt content. The content of soil salt ions showed that the types of main salt ions in each soil layer were stable. The seasonal distribution pattern demonstrated that the contents of K^+, Na^+, Cl^-, and SO_4^{2-} in spring, autumn, and winter were significantly higher than that in summer, which was consistent with the dynamics of total salt. The HCO_3^- content peaked in spring followed by autumn and maintained a relatively low level in winter and summer. Mg^{2+} exhibited significant seasonal fluctuations, while Ca^{2+} also showed discernible seasonal differences (Figure 7). The distribution characteristics of the ion confirmed the regulatory effect of water-salt movement on the seasonal migration of salt. The typical correlation analysis revealed that there was seasonal differentiation in the dynamic controlled mechanism of soil salinity. TS was always dominated by Cl^-, and its control intensity showed an increasing trend of spring > winter > autumn > summer with the change of seasons. In spring, TS was simultaneously affected by the synergistic effect of Mg^{2+} and Na^+. In summer, the contribution of HCO_3^- was weak. In autumn, new SO_4^{2-} had a synergistic effect. EC was independent of the main ions in spring, became dominated by Mg^{2+} and Ca^{2+} in summer, and was controlled by Na^+ in autumn. SAR was regulated by HCO_3^- in spring, dominated by K^+ in summer, and was free from significant ionic influence in autumn. Furthermore, the spatial distribution of

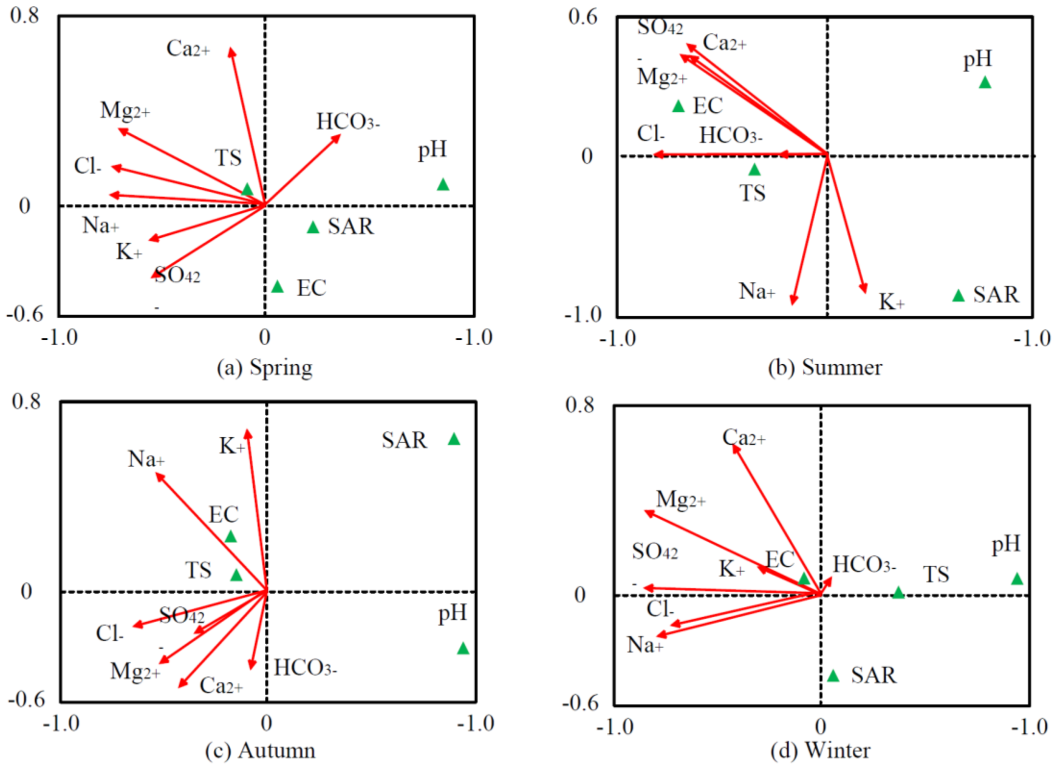

Figure 8. Two-dimensional CCA ranking diagrams of soil salinity in different seasons.

pH values was uniform and not significantly disturbed by environmental factors (Figure 8). This rule confirmed that rainfall and irrigation differentially regulated the seasonal migration process of various salt ions by driving the movement of water and salt.

Discussion

The impact of irrigation on soil salinization

This study found that, under the hydrological characteristics of "spring drought and summer flood" in Cangzhou, Hebei, China, irrigation could temporarily alleviate crop water demand and reduce surface salinity, but it led to salt accumulation in the deep soil layer of 40 - 60 cm, which was related to the limited water infiltration depth and hindered salt transport under traditional flood irrigation. The leaching effect of heavy summer rainfall could partially offset this risk. Compared with the research of Gao *et al*. on the coastal saline-alkali land in Hebei, China, which achieved safe utilization of saline irrigation through a subsurface drainage system, this study emphasized the potential risk of saline irrigation under no-drainage conditions, i.e., deep salt accumulation might cause long-term soil degradation [16]. Furthermore, the shallow drainage technique developed by Saleh *et al*. reduced salt content by 60%, suggesting that the synergistic effect of natural rainfall leaching and artificial irrigation needed to be matched with soil profile characteristics [17].

Threshold effect of rainfall leaching and seasonal salt dynamics

Soil salinity in Cangzhou, Hebei, China exhibited a pattern of "spring salt return - summer desalination - autumn/winter salt accumulation". Continuous summer rainfall reduced surface salinity, lowered pH throughout the profile, and reached a leaching depth of 60 cm. The freeze-thaw cycle study conducted by Wu *et al*. showed that snowmelt infiltration reduced surface salt content. The present study showed that, through continuous leaching and deep infiltration, rainfall achieved a desalination rate of 38.2% in the 40 - 60 cm soil layer, highlighting the driving effect of rainfall on vertical salt transport [18]. In addition, canonical correlation analysis indicated that Cl^- and Na^+ were the core ions driving seasonal salt dynamics with higher contents in autumn and winter than in spring and summer. This result was consistent with the conclusion drawn by Mathinya *et al*. that shallow groundwater depth exacerbated surface accumulation of Cl^-. However, this study further revealed the timeliness of rainfall in reducing ion concentrations through dilution [19]. In the coastal saline-alkali land of Cangzhou, Hebei, China, due to the shallow burial depth and high mineralization of groundwater, salt was prone to move upward *via* capillary action. Previous studies have confirmed that the combined application of subsurface drainage and rainy-season leaching can effectively break the vicious cycle of “salt following water”. However, generalizing this strategy needs to consider the differences in regional hydrological annual patterns, which include that, in wet years, leaching efficiency is high, whereas in dry years, supplemental irrigation is required, even it may exacerbate salt inputs. Future research should combine dynamic models to simulate salt flux thresholds under different climate scenarios and explore the integrated application of salt-tolerant crop breeding and water-saving irrigation technologies.

Acknowledgements

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