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SALINITY ANALYSIS OF DESERT WETLAND SOILS IN EXTREMELY ARID REGIONS

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ABSTRACT

The Xihu desert wetland of Dunhuang (Gansu province) has the dual features of an extremely arid desert ecosystem and wetland ecosystem and plays a particularly important role in China. However, research on soil salinity in this region is very rare. This study collected samples of different soil types in the Xihu desert wetland ecosystem and analyzed the soil salinity characteristics at different sites. This study provides theoretical and data support for the assessment of soil salinization, ecological restoration and sustainable use of desert wetlands. According to the results, of the eight types of ions in the Xihu desert wetland soils, Na^+, Ca^{2+}, Mg^{2+} and K^+ dominate the positive ions, while SO_4^{2-}, Cl^- and HCO_3^- dominate the negative ions, but CO_3^{2-} was not detected. Na^+ had the highest positive ion concentration, while K^+ had the lowest concen- tration. Na^+ was mainly present in the form of sodium and calcium salts. SO_4^{2-} had the highest negative ion concentration, while HCO_3^{2-} had the lowest concentration. The salinity is mainly contri- buted by Na_2SO_4 and $CaSO_4$. The correlation analysis of the salt ions in the Xihu desert wetland soils suggested that there were correlations between the different salt ions in the soil and these reflected the sedimentation characteristics of the salts. The cluster analysis of soil salt ions showed that salinity analysis could be restricted to just three ions (Ca^{2+}, Cl^-, and SO_4^{2-}) and these ions would sufficiently reflect the changes in the various salt contents in the Xihu desert wetland. The formation of saline soil in the research area was due to the combined actions of parent material, landform and hydrogeology.

KEYWORDS:
Extremely arid region; desert wetland; salt ions; salinization; characteristic analysis

INTRODUCTION

Soil is very complex and changes with spatial position under the influence of climate, biology, parent material, landform and formation time [1,2,3,4,5,6]. Soil salinization often occurs in regions with an arid climate, high soil evaporation and high underground water levels. These conditions are due to natural factors, such as climate, landform and hydrogeology [7,8,9,10,11]. They are also the result of land deterioration caused by excess human activities and a fragile ecological environment [12,13,14]. When the salts in the soil have accumulated to a critical level, they will restrict the ability of crop roots to absorb water and nutrients, and plant root growth. This affects the normal development and growth of plants. Soil salinization also affects soil productivity and leads to severe agricultural production losses. Moreover, salt accumulation changes the plant growth environment and results in the dominance of saline and desert plants, thus ultimately leading to the deterioration of the ecological environment [15,16]. At present, salinized soil is widely distributed in around 100 countries and regions, covering an area of 10×10^8 hm^2 [17]. About 7, 700×10^4 hm^2 of salinized soil has been caused by human activities [18] and due to the serious impact on economic and ecological systems, salinization is beginning to receive more attention from the public [4,5,10,11,19].

Located in northwest China's arid extremely region, the Xihu desert wetland ecosystem is a typical example of a desert and wetland ecosystem in an arid region. Occupying a highly significant position in China, it is a natural laboratory for carrying out various studies on desert wetland ecosystems [20,21]. In recent years, because of the combination of climate change and human activities, the Xihu desert wetland ecosystem has been confronted with a series of environmental problems, such as water shortage, declining groundwater levels, desertification, soil salinization and a decrease in wetland area. However, due to natural

TABLE 1
Geographic location details for the sampling points

Plot name	Geographical coordinates	Altitude	Soil and vegetation
Plot 1	40°20.179′N, 93°44.420′E	1005 m	The soil type was marsh soil; vegetation was dominated by *Phragmites communis*.
Plot 2	40°20.282′N, 93°44.102′E	1008 m	The soil type was marsh soil; vegetation was dominated by *Phragmites communis*.
Plot 3	40°20.797′N, 93°42.861′E	1004 m	The soil type was meadow soil; vegetation was dominated by low *Phragmites communis* and *Alhagi sparsifolia*.
Plot 4	40°20.730′N, 93°42.736′E	1000 m	The soil type was marsh soil; salinity was serious with a crust layer; vegetation was dominated by low *Phragmites communis* and *Nitraria tangutorum*.
Plot 5	40°20.563′N, 93°42.308′E	1007 m	Located in HouKeng ecological restoration area; the soil type was marsh soil and meadow soil; vegetation was dominated by *Alhagi sparsifolia* and *Glycyrrhiza*.
Plot 6	40°20.747′N, 93°41.353′E	993 m	Located in the lake; the soil type was marsh soil; salinity was serious; vegetation was *Hsuaeda salsa*.
Plot 7	40°19.134′N, 93°39.495′E	1004 m	Gobi Desert; vegetation was dominated by *Alhagi sparsifolia*; *Glycyrrhiza*; *Nitraria tangutorum* and *Calligonum* were sporadically distributed
Plot 8	40°16.320′N, 93°26.200′E	943 m	Severe desertification; vegetation was *Populus euphratica* and low *Phragmites communis*.

condition limitations, there has been very little research on soil salinity in this region. This study provides a better understanding of the soil characteristics in this region and gives theoretical and data support for soil salinity assessment in desert wetlands, vegetation recovery and recons- truction, sustainable use of wetlands and regional ecological protection.

MATERIALS AND METHODS

Sites description. The Xihu desert wetland is located at the western end of the Hexi corridor, Gansu Province, which is approximately 120 km from Dunhuang city. It borders the Kumtagh Desert to the west, Aksai Kazakh autonomous county to the south and Xinjiang Uygur Autonomous Region to the north. It covers an area of 6.6×10^8 m^2 (92° 45′E-93°50′E, 39°45′N-40°36′N). The topography is low in the north and high in the south and the center is an alluvial plain surrounded by the Gobi Desert. It has an extremely dry temperate continental climate. The annual average temperature is 9.90°C, the lowest temperature is −30°C and the highest temperature is 40°C. Average annual precipitation is 39.90 mm and evaporation is 2,486 mm. Annual total sunshine is 3,115-3,246.70 h and the sunshine rate is 70%-73%. The total radiation is 641.84 kJ cm^{-1}, the average wind velocity is 2.20 m s^{-1} and the mean annual number of days with gales is 15.4 d. The dryness degree is greater than 16 [21,22]. The flora belongs to the Asia desert sub-region [21] and is temperate desert in nature, which reflects the plant distribution characteristics and adaptions to the regional climate [23]. The main plants include *Lycium ruthenicum*, *Alhagi sparsifolia* and *Phragmites communis* and associated plants include *Leymus secalimus*, *Carex orbicularis* and *Salsola collina*. Soil types are mainly marsh soil, meadow soil and saline alkaline soil [24].

Plot selection and soil sampling. Soil samples were collected according to landform, soil type, vegetation, etc. Eight sampling sites were selected using an “S”-shaped sampling method. The depth of each sampling point depth was 100 cm, with soil taken in columnar samples (20 cm long drill bit, drill body length 100 cm). Samples were collected in 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm layers. GPS was used to determine the longitude, latitude and altitude of each site. The geographic locations, altitudes and vegetation for the sampling points are listed in Table 1.

Soil chemical analysis. After the soil samples were air dried in the laboratory, intrusions other than soil were eliminated (e.g. plant residues, stones, bricks and other impurities). The air-dried soil was passed through a 1-mm sieve, and 10 g of soil sample and 25 g of distilled water (at a water/soil ratio of 2.5:1) were blended. After shaking and centrifugation, the supernatant was collected for determination of pH value, soil salinity and composition. The pH value was determined by a LP-115 pH Meter; CO_3^{2-} and HCO_3^- were determined by double-tracer neutralization; Cl^- was determined by $AgNO_3$ titration; SO_4^{2-} was determined by EDTA-indirect titration; Ca^{2+} and Mg^{2+} were determined by EDTA complexometric titration and K^+ and Na^+ were determined by subtraction.

Total content of soluble salts in the soil The K^+, Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-} and Cl^- contents in the soil leaching liquor were determined. The sum of the respective contents of these ions was the total amount of soluble salts in the soil.

Data processing. Excel 2010 was used to input the soil sample data and IBM SPSS statistics 20 analysis software was used to conduct correlation and statistical analyses of the soil nutrients. The charts were plotted using Origin 8.0.

RESULTS AND ANALYSIS

Composition and types of soil salinity. The major components of the soluble salts in the soil samples were HCO_3^-, Cl^-, SO_4^{2-}, CO_3^{2-}, Ca^{2+}, Mg^{2+}, K^+ and Na^+. Theoretically, the total molar quantity of positive ions (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and negative ions (HCO_3^-, Cl^-, SO_4^{2-} and CO_3^{2-}) should be in a balanced state. However, in reality, there are large errors in using the traditional volumetric method to determine the calcium, magnesium and sulfate contents at extremely low or high amounts. Therefore, it is hard to achieve a balance between the positive and negative ions in the samples and errors are unavoidable [25]. The proportions of the eight major ions in Xihu desert wetland soils are shown in Figure 1. According to Figure 1, Na^+ has the highest positive ion content, while K^+ has the lowest content, whereas SO_4^{2-} has the highest negative ion content, and CO_3^{2-} was not detected in the test. HCO_3^-, the lowest detectable negative ion, only accounted for 0.3% of the total salt content. There were 12 types of salts in the Xihu desert wetland soils, namely, soluble salts (NaCl, Na_2SO_4, $MgSO_4$, Na_2CO_3, $NaHCO_3$, $MgCl_2$ and $CaCl_2$), a moderately soluble salt ($CaSO_4$), two slightly soluble salts ($Ca(HCO_3)_2$ and $Mg(HCO_3)_2$) and two insoluble salts ($CaCO_3$ and $MgCO_3$). Sodium and calcium salts were the dominant components of the total salt content and were mainly in the form of Na_2SO_4, $CaSO_4$, $NaHCO_3$ and $Ca(HCO_3)_2$.

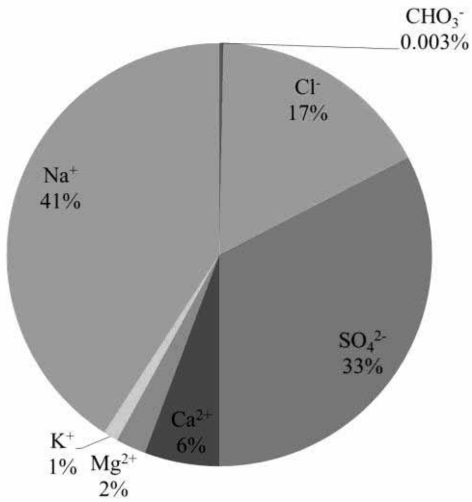

FIGURE 1
The percentage components of the eight ions in the total salt content

Correlation analysis of the inorganic ions in the soil. The correlations between the inorganic ions in soils can provide a scientific basis for the prevention and improvement of salinized soil [26]. This research conducted a correlation analysis on the concentrations of inorganic ions in soil samples taken from the Xihu desert wetland ecosystem (Table 2).

TABLE 2
Correlation coefficients between the various inorganic ions

	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
HCO_3^-	1						
Cl^-	0.273	1					
SO_4^{2-}	0.421**	0.828**	1				
Ca^{2+}	0.089	0.497**	0.687**	1			
Mg^{2+}	0.353*	0.446**	0.611**	0.539**	1		
K^+	0.276	0.603**	0.706**	0.690**	0.511**	1	
Na^+	0.377*	0.951**	0.951**	0.557**	0.492**	0.641**	1

*The significance level was set at 0.05 (2-tailed).
**The significance level was set at 0.01 (2-tailed).

TABLE 3
Statistical results for the frequency distributions of the different salt ions

Statistical item	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	Total salt
Mean (cmol kg^{-1})	.4041	21.7088	41.4428	7.2516	2.9175	1.4234	51.9845	130.2090
Std. Error of Mean (cmol kg^{-1})	.02532	4.86603	6.85445	.85096	.76311	.32831	10.07476	22.77618
Median (cmol kg^{-1})	.3813a	9.5233a	25.8800a	7.5100a	1.6300a	.6233a	29.6750a	76.0200a
Mode (cmol kg^{-1})	.27b	10.81	53.90	.15	.05b	.56	23.08	3.15b
Variance (cmol^2 kg^{-2})	.027	994.485	1973.308	30.414	24.458	4.527	4263.035	21268.924
Skewness	.934	2.521	1.520	1.164	3.343	2.613	2.016	1.830
Kurtosis	2.548	6.120	1.425	2.642	11.685	6.750	3.612	2.623
Minimum (cmol kg^{-1})	.19	.56	.25	.15	.05	.05	1.27	565.14
Maximum (cmol kg^{-1})	.93	135.60	167.05	26.36	24.35	9.77	262.50	3.15

*Note: In Table 3, 'a' represents the minimum values of the various mode values.

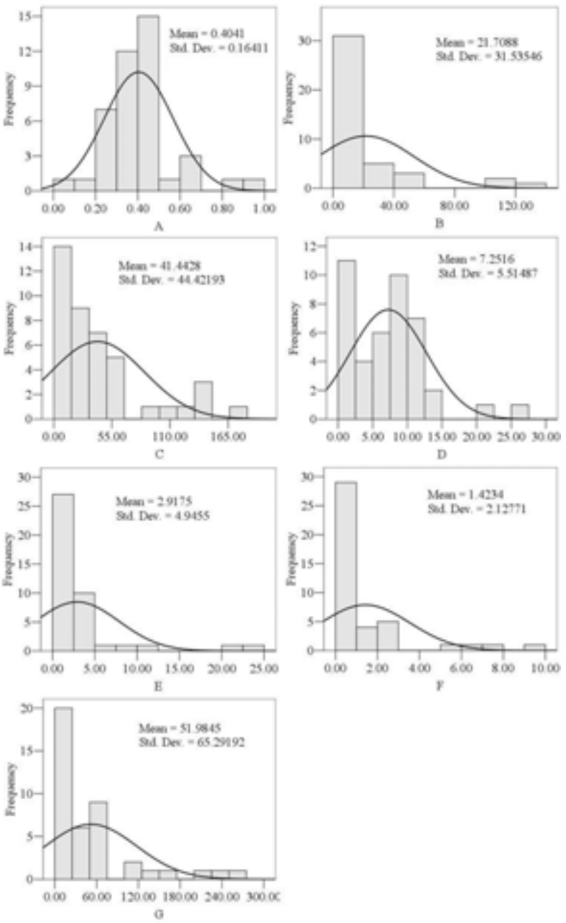

FIGURE 2
Frequency distribution of salt ions (A, HCO_3^-; B, Cl^-; C, SO_4^{2-}; D, Ca^{2+}; E, Mg^{2+}; F, K^+; G, Na^+)

There was an extremely significant positive correlation between HCO_3^- and SO_4^{2-}. They were also significantly correlated with Mg^{2+} and Na^+, which suggested that the HCO_3^- content rose as the SO_4^{2-}, Mg^{2+}, and Na^+ levels increased. Cl^- had an extremely significant positive correlation with SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+ and Na^+ and SO_4^{2-} had an extremely significant positive correlation with Ca^{2+}, Mg^{2+}, K^+ and Na^+. This suggested that in the soil profile, the lower soil layers, which had accumulated HCO_3^-, Cl^- and SO_4^{2-}, had developed the characteristics of a neutral soil. This had led to the accumulation of Ca^{2+}, Mg^{2+}, K^+ and Na^+. There were extremely significant correlations between Ca^{2+} and Mg^{2+}, K^+ and Na^+ and between Mg^{2+}, K^+ and Na^+. These results showed that correlations exist between different inorganic ions in the soil and that they reflect the sedimentary characteristics of salt.

Frequency distribution analysis of the inorganic ions in the soil. There is a chemical relationship between various inorganic ions in the soil. Frequency distribution can reflect the distribution of the samples as a whole [26]. Table 3 and Figure 2 show the results for the soluble inorganic ion frequency distribution analysis of the Xihu desert wetland soils.

The statistical analysis of the test data (Table 3) showed that the characteristic values for soil salinity at each sampling point in the research area were significantly different The salt content in the soil ranged from 3.15 to 565.14 cmol kg^{-1} and the average value was 130.21 cmol kg^{-1}, which suggested that the soils in the research area were principally saline soils. Figure 2 shows the variation patterns for the different salt contents in the various soil layers. Although there were a few differences between the saline ions, their frequency distri- butions were roughly symmetrically or incomple- tely symmetrically unimodal. The HCO_3^- content basically had a normal distribution and the Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, K^+ and Na^+ contents were posi- tively skewed (asymmetrical, right-skewed). The average value for each inorganic ion in Figure 2 indicates the composition of the inorganic ions in Xihu desert wetland soils. The main negative ion is SO_4^{2-}, which had a soil content of 41.44 cmol kg^{-1}, and accounted for 65% of the total ion content. Cl^- is next, with a content of 21.71 cmol kg^{-1} and accounted for the 34% of the total content of negative ions. The main positive ion was Na^+ with a content of 51.98 cmol kg^{-1}, which accounted for 82% of the total content of positive ions. The variation in the soil salt contents across the region may be due to the different ion compositions of the various soil parent materials and by underground water.

Cluster analysis of the inorganic ions in the soil samples. There are many variables that can affect the characteristics of an object. Research is often conducted on a certain set variables that are dependent on the specific research issue. Due to limited understanding of objects, it is often difficult to find independent representative variables, which affects further understanding and research. Cluster analysis can cluster the observed variables of the research object based on the closeness of the relationships between the variables, grouping those with common characteristics into one type. To this end, this study analyzed the relationships between the seven quantitative indicators (excluding CO_3^{2-}) for inorganic ions in the Xihu desert wetland soils using nearest neighbor clustering.

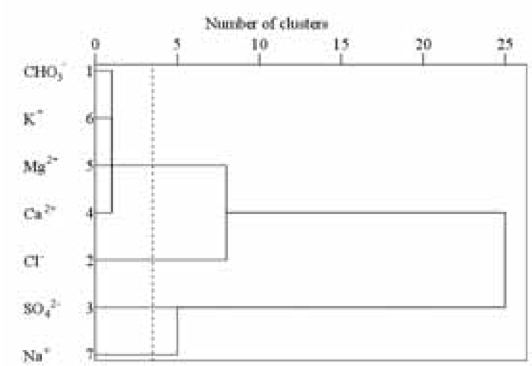

FIGURE 3
Dendrogram of the cluster analysis based on correlation coefficients

According to Figure 3, a distance threshold of 3.5 was the classification standard. The seven saline ions were classified into three cluster types: type I: HCO_3^-, Mg^{2+}, K^+ and Ca^{2+}; type II: Cl^- and type III: SO_4^{2-} and Na^+. Therefore, according to the cluster analysis results, analyses can be confined to three ions, one taken from each cluster type, as they reflect the changes in various saline ions in farmland if the sample size is large enough. This method can reduce the workload without missing useful information. Three saline ions were selected, namely Ca^{2+}, Cl^- and Na^+.

DISCUSSION AND CONCLUSION

The salinized soil in the research area is the outcome of the combined actions of parent material, climate, landform, hydrogeology and biology.

(1) Parent material: the research area is located at the end of the Shule River. Most parent materials are alluvial in nature and the salt they contain has accumulated over a long geological period. Due to frequent gales, strong evaporation and weak eluviation, the salt has moved up to the ground surface under the capillary force effect. As a result, most soil parent materials contain salt, which has led to primary salinization of the soil in the research area.

(2) Water resources and hydrogeological conditions: the water sources in the Xihu wetlands are mainly formed when the subsurface flow, caused by precipitation, mixes with the glacial snowmelt from the Shule River, Danghe River, West Qilian Mountain and East Aerjin Mountain. With the growth in population, the development of a social economy and constant expansion of agricultural irrigation areas, water resource utilization has gradually turned from natural utilization to artificial utilization. The inadequacy of the surface water resource compels people to dig wells to exploit underground water. The digging of more wells with greater depths has caused a sharp drop in the groundwater level. The underground water storage space in this area is mainly the space formed by the unconsolidated quaternary deposit, which is distributed in the terraces and alluvial fan areas at an altitude of 1000–2000 m and at a depth of 3–100 m. The degree of mineralization is quite high, at 1–16 g L^{-1}. The salinity is mainly caused by sulfates or chloride and sulfates and the water is mainly saline and brackish.

(3) Soil texture: Differences in soil textures are associated with different porosities, which, in turn, affects the salt accumulation process. The research area is located at the end of the Shule River. The low-lying strata have high clay particle contents, which affects groundwater runoff, and the water is under high pressure, as shown by capillary pressure test results for the area and the small critical depth. This makes it extremely easy to transport various salts to the surface and cause salinification.

Through analysis and discussion of the salt characteristics in the different layers of the Xihu desert wetland ecosystem, the following con- clusions can be drawn. Among the eight major ions in the Xihu desert wetland ecosystem, SO_4^{2-}, Cl^- and HCO_3^- were the main negative ions, while CO_3^{2-} was not detected. Na^+, Ca^{2+}, Mg^{2+} and K^+ were the main positive ions. SO_4^{2-} had the highest negative ion concentration, while HCO_3^{2-} had the lowest. Na^+ had the highest positive ion concentration, while K^+ had the lowest. The salts were mainly sodium and calcium salts, typically Na_2SO_4 and $CaSO_4$. The soils in the research area were mainly saline soils. According to the correlation analysis of the inorganic ions, there were some correlations between the different saline ions in the soil, which reflected the sedimentary characteristics of salt. The cluster analysis of the inorganic ions in soil showed that the analyses of only three ions, one from each cluster type (Ca^{2+}, Cl^{-}, and Na^{+} were chosen) sufficiently reflected the changes in various salt ion levels in the Xihu desert wetland soils. Finally, the formation of salinized soil was caused by the combined action of a number of factors, such as parent material, climate, landform and hydrogeological conditions.

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