

Article

Infiltration and Leaching Characteristics of Soils with Different Salinity under Fertilizer Irrigation

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Abstract: Salt and nutrient transport and transformations during water infiltration directly influence saline soil improvement and the efficient use of water and fertilizer resources. The effects of soil initial salinity (18.3 g/kg, 25.5 g/kg, 42.2 g/kg, 79.94 g/kg, and 165 g/kg, respectively, labeled S1 to S5) on the infiltration and leaching characteristics of water, salt, and nitrogen were analyzed via a one-dimensional vertical fertilizer infiltration experiment. Meanwhile, the estimation models of cumulative infiltration and wetting front, including the effect of soil initial salinity, were established. The results showed that, with the increase in soil initial salinity, the cumulative infiltration within the same time decreased, and the migration time of wet front to 45 cm was longer. The time required for S5 to reach the preset cumulative infiltration was more than six times that of S1, and, for the wet front migration to 45 cm, the time requirement for S5 was about four times that of S1. In the established Kostikov model and wetting front model, the coefficients all decreased with the increase in soil initial salinity, and the test index R^2 values both reached 0.999. In the Kostikov model, coefficient K had a linear relationship with the natural logarithm of initial soil salt content, while index a had a direct linear relationship with initial soil salt content. The cumulative leachate volume decreased with the increase in soil initial salinity, and the corresponding data of S3 and S5 were reduced by 37% and 57.3%, respectively, compared with S1. The electrical conductivity values of S1, S3, and S5 were 15.4, 209.8, and 205.6 ms/cm, respectively, being affected by the initial content in soil, soil moisture transport rate, and exogenous potassium nitrate (KNO_3) addition. The NO_3^- -N concentrations in the leachates of S1, S3, and S5 at the end of leaching were 55.26, 16.17, and 3.2 mg/L, respectively. Based on the results of this study, for soil with high initial salinity, the conventional irrigation amount (2250 m^3/ha) of the general soil in the study area could not meet the requirements of leaching salt. These results can provide a reference for the formulation of irrigation and fertilization strategies for soils with different salinity and contribute to the sustainable development of saline soil agriculture and the ecological environment.

Keywords: soil initial salinity; cumulative infiltration; Kostikov model; leaching solution; NH_4^+ -N and NO_3^- -N



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1. Introduction

At present, approximately 1 billion m^2 of land globally is affected by salinization, accounting for more than 20% of agricultural land, of which 12% is located in China [1]. Despite most salinization being caused by natural geochemical processes, it is estimated that 30% of irrigated land globally suffers from human-induced secondary salinization, such as the application of poor-quality irrigation water, land degradation in facility agriculture,

and other factors [2]. These soils are characterized by high soluble salt content ($>0.3\%$), which exists in the form of ions in the pore solution of the charged soil under the action of water and reacts physically and chemically with clay particles [3]. When the salt content changes, the micro-electric field on the surface of clay particles changes, causing changes in bound water content, pore size distribution, particle shape, and structural connection, which adversely affects soil physicochemical properties and ultimately affects water and nutrient uptake by crops [4–6]. As freshwater resources for irrigation decrease, land degradation, frequent droughts, and the global population continue to increase, and the salt-affected soil area is expected to increase significantly [7,8]. Soil salinization has seriously affected sustainable land use, arable land fertility, and food security [9], making it one of the largest challenges faced by agricultural production and environmental sustainable development [10]. Therefore, the improvement and utilization of saline soils have attracted extensive global attention. How to adjust the fertility of saline soils through irrigation and fertilization, make full use of limited water and fertilizer resources, and ensure arable land and food security have become important topics of concern in saline arid areas all over the world.

Water infiltration is one of the key components of the soil water cycle in the field [11,12]. Soil infiltration capacity directly affects the transport speed and size of precipitation and irrigation water [13], significantly influencing irrigation water use efficiency. In saline soils, excessive exchangeable sodium destroys the physical structure of the soil by inducing dispersion and outward diffusion of clay particles [14], resulting in reduced infiltration capacity. Reducing the percentage of exchangeable sodium ions could improve soil hydraulic conductivity [15]. The Kostiakov model, a classical infiltration model, is widely used for various soil types to determine the time required for water to penetrate soil and facilitate improvement in water-saving irrigation designs. High salinity usually causes soil particles to bind tightly, reducing porosity and thus reducing the rate of water infiltration. Therefore, when applying the Kostiakov model to soils with different initial salinity, the influences of these factors should be considered [16]. Through experiments and model simulations, the researchers explored the effects of different initial salinity on the parameters of the Kostiakov model. Liu et al. (2023) showed that the Kostiakov model could well simulate the infiltration characteristics of soil water between layers with different profile configurations of saline–alkali soil. Meanwhile, the study found that the cumulative infiltration of low-salinity soil layers had a large slope over time, but the slope slowed down when encountering high-salinity soil layers [17]. Aboukarima et al. (2018) studied the effects of the sodium adsorption ratio (SAR) and electrical conductivity (EC) of irrigation water quality on the parameters of Kostiakov’s infiltration model [18]. Molayem et al. (2021) found in a study on soil in southern Iran that the infiltration coefficient and index parameters of Kostiakov’s model changed with an increase in soil initial salinity, which reflected the effect of salinity on water movement [19]. However, the applicability and accuracy of Kostiakov’s model for different soil types and saline soil under different environmental conditions still need to be further studied and explored. To clarify the relationship between initial salt content (salinity) and infiltration characteristics (i.e., cumulative infiltration and wetting front) of natural soil, it would be helpful to formulate targeted water management strategies for saline soil and ensure a rational irrigation schedule.

Meanwhile, the infiltration process is accompanied by the migration and transformation of salt and nutrients, and rainfall or irrigation may lead to the leaching of salt and nutrients along with water [12]. Leaching is one of the main causes of water and fertilizer loss in farmland. Excessive irrigation and fertilization not only cause resource waste but may also lead to environmental problems such as increased salinity and eutrophication in groundwater, increasing the risk of non-point source pollution [20,21]. However, salt leaching is necessary to maintain agricultural production in saline fields [22], with the aim of maintaining root zone salinity at a level that avoids crop growth or yield reduction [10,23]. Yang et al. (2023) studied the influence of different soil texture and irrigation methods on leaching efficiency and showed that different water application methods had a greater

influence on the leaching efficiency of coarse soil than that of fine soil [23]. Yin et al. (2022) explored the leaching characteristics of salt in high-saline soil regarding Yellow River water and brackish water and found that the soil salinity values after the leaching of Yellow River water and brackish water were only 21.01% and 31.96% of the initial salinity [24]. The salt leaching also caused loss of water and fertilizer, but the current research on the leaching rules of water, salt, and nitrogen in soils with different initial salinity under irrigation and fertilization conditions still faces challenges [25–27], especially when soil type, structure, and environmental conditions are considered; the characteristics of leachate volume and solute content changes become more complicated. To understand the influence of soil initial salinity on water and nutrient leaching characteristics under irrigation, one may evaluate the effect of salt leaching and influence of irrigation and fertilization strategy on the quality of deep soil or groundwater and reduce the salt and nitrogen complex loads of deep soil–groundwater systems by leaching [28–30].

Xinjiang has long sunshine hours, sufficient light, and significant diurnal temperature differences, which are ideal conditions for plant growth, making it an important cotton production base in China [31]. However, the region has little rainfall and high soil evaporation during the growing season, resulting in serious soil salinization, which affects the holding capacity of soil water and fertilizer, posing a threat to crop growth and food security, and its regional economic development and environmental improvement face challenges from soil salinization and water shortages [32,33]. In order to make rational use of saline soil resources, improve the utilization efficiency of irrigation water and fertilizer, and minimize the occurrence of adverse environmental impacts, this study aimed to (1) explore the impact of soil initial salinity on water infiltration and establish estimation models for the cumulative infiltration and wetting front aspects of soils with different salinity and (2) examine the leaching characteristics of these soils, thereby revealing how soil initial salinity affects the infiltration capacity and leaching characteristics of water, salt, and nitrogen. These findings will offer significant insights for improving saline soils and efficient utilization of water and fertilizer resources in arid and semi-arid areas, and contribute to the sustainable use and management of saline lands in the Xinjiang region and other similar areas.

2. Materials and Methods

2.1. Test Material

The test saline soil samples were sourced from Korla region in southern Xinjiang Province. Through preliminary investigation, 0–20 cm surface soil was collected from 4 regions with different soil salinity, which were labeled S1, S2, S3, and S5. S4 is configured soil, disturbed soil, which is obtained by mixing S3 and S5 soils at a ratio of 1:2. Collected soil samples were naturally air-dried, milled, and removed of impurities. After 2 mm screening, the soil particle gradation and basic physicochemical property were determined. The results are shown in Tables 1 and 2.

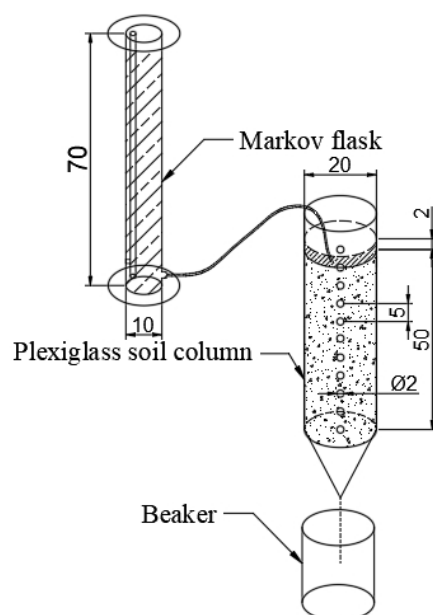
Table 1. Particle grading of the test soil.

Soil Number	Soil Particle Analysis/%			Soil Type
	Clay	Silt	Sand	
salty soil S1	2.79	13.34	83.87	Loamy sandy
salty soil S2	3.73	17.48	78.79	Loamy sandy
salty soil S3	3.02	14.73	82.25	Loamy sandy
salty soil S4	4.92	21.34	73.74	Sandy loam
salty soil S5	6.92	27.88	65.20	Sandy loam

Table 2. Basic physical and chemical properties of the test soil.

Soil Number	pH	Electric Conductivity (ms/cm)	Salt Content (g/kg)	Organic Matter (g/kg)	Total N (g/kg)	NO ₃ ⁻ -N (mg/kg)	NH ₄ ⁺ -N (mg/kg)
S1	8.01	2.43	18.3	11.13	0.57	177.48	6
S2	7.59	3.41	25.5	11.28	0.50	321.19	5.7
S3	8.3	10.22	42.2	5.12	0.19	49.9	4.59
S4	7.72	18.95	79.94	10.37	0.26	23.09	13.85
S5	7.72	38.8	165	12.49	0.34	4.45	24.94

Nitrogen (N) is one of the most required mineral elements for plant growth, and potassium (K) plays a vital role in nitrogen metabolism, both elements being widely applied as fertilizers in agricultural production [34]. KNO₃ is a stable potassium–nitrogen compound fertilizer, which can provide essential potassium and nitrogen for crop growth at the same time [35]. Therefore, KNO₃ was selected as the test fertilizer in this study, and it was dissolved in water for the one-dimensional vertical fertilizer infiltration experiment. The infiltration test device consists of a Markov flask and a soil column made of transparent plexiglass, as shown in Figure 1. The inner diameter of the soil column is 20 cm, the height is 60 cm, and the two sides are symmetrically equipped with circular holes with a diameter of 2 cm, optimal to fetch soil. The distance between the center of the circle is 5 cm. The bottom of the soil column is provided with air holes to collect the bottom leachate. The inside of the bottle is 10 cm straight and 70 cm high, and the soil column is supplied with water through a rubber tube. The inside of the bottle is 10 cm straight and 70 cm high, and the soil column is supplied with water through a rubber tube.

**Figure 1.** Schematic diagram of soil column test device.

2.2. One-Dimensional Vertical Fertilizer Infiltration Test

The soil columns were filled according to the actual soil conditions in the sampling area, the bulk density was set at 1.35 g/cm³, and the depth was 50 cm. The soil was compacted every 5 cm to prevent the formation of large pores. Combined with the average moisture content of the air-dried soil, the total filling mass of the soil was calculated to be 21.2 kg. The conventional mass concentration of KNO₃ applied in Xinjiang was 600 mg/L, the irrigation quota was 2250 m³/ha, and the irrigation amount in this experiment was about 7 L. The infiltration test was repeated twice for each column of saline soil.

During infiltration process, the head control was maintained at a constant 2 cm. Beakers were placed under the soil columns to collect the leachate. At the beginning of the experiment, the position of the wetting front and the Markov flask's water level were recorded according to the principle of first dense and then thinning. Soil samples were collected from the small side holes of the soil column when the wetting front reached 5, 15, 25, 35, and 45 cm. At the end of infiltration, soil samples were also taken from the above five depths. In this test, the water supply of S1, S3, and S5 at the end of infiltration was the same, which is 6.8 L, and the cumulative infiltration volume of S2 and S4 soil columns at the end of infiltration is 7 L. Each sample was repeated 3 times to measure soil moisture, pH, conductivity, salinity, and contents of ammonium nitrogen and nitrate nitrogen.

During the test, the leached liquid was collected every 1 h after leachate began to appear at the bottom of the soil column, and every 1 d after infiltration until no leached liquid was produced. The leachate's volume was recorded, and its conductivity, ammonium nitrogen, and nitrate nitrogen concentrations were measured.

2.3. Measuring Indexes and Methods

Soil water content was determined by drying method. The soil total nitrogen was determined by Shimadzu gas chromatograph (GC-2014C, Shimadzu (China) Co., LTD., Shanghai, China). Soil organic matter was determined by Shimadzu total organic carbon analyzer (TOC-L, Shimadzu (China) Co., LTD., Shanghai, China). The total salt content was determined by drying residue method, where soil was mixed with deionized water according to the soil–water ratio of 1:5. Further, 25 mL of the extract was baked in a constant temperature drying oven at 105 °C for 2 h, and then steamed in a water bath to measure the change in the total salt. The soil conductivity was measured by an electrical conductivity meter (HQ14d, American HACH (China) Co., LTD., Shanghai, China), and the soil solution was prepared according to the soil–water ratio of 1:5, and then measured after oscillation and filtration. Soil pH was determined with a pH meter (PHSJ-5T, Shanghai Yidian Science Instrument Co., LTD., Shanghai, China). Soil particle composition was determined by Mastersizer-2000 laser particle size analyzer (MS2000, Malvern Panalytical Ltd., Malvern, UK). An automatic discontinuous chemical analyzer (Smartchem450, Kpmann Analytical Instruments (Beijing) Co., LTD., Beijing, China) was used to determine ammonium nitrogen $\text{NH}_4^+\text{-N}$ and nitrate nitrogen $\text{NO}_3^-\text{-N}$, and soil samples were soaked with KCl solution.

2.4. Data Analysis

Excel was used to sort out and analyze the test data. SPSS was used to analyze the data significance. Origin 2018 was used for graphs. The coefficient of determination (R^2) and the coefficient of determination (r) [36,37] were selected as assessment indicators to evaluate the accuracy of the empirical model developed in this study. The closer the R^2 is to 1, the higher the accuracy of the fitting model. The value of r ranges from -1 to 1 . The greater the $|r|$, the stronger the correlation.

3. Results and Analysis

3.1. Infiltration Characteristic

3.1.1. Cumulative Infiltration

Figure 2 shows the change in the mean cumulative infiltration of different soils with infiltration time. Under different initial salinity conditions, with the increase in time, the cumulative infiltration of each treatment has a significant difference. However, in the initial stage of infiltration, the gradient of water potential is large, and the cumulative infiltration increases rapidly. However, the cumulative infiltration at the same time has a decreasing trend with higher soil initial salinity. It took 460 min, 800 min, 600 min, 1260 min, and 2880 min for soils with different initial salinity (S1 to S5) to reach the cumulative infiltration of 21.7 cm, and the time required for S5 was more than six times that of S1, which indicates that the initial salinity of soil has a greater impact on the cumulative infiltration.

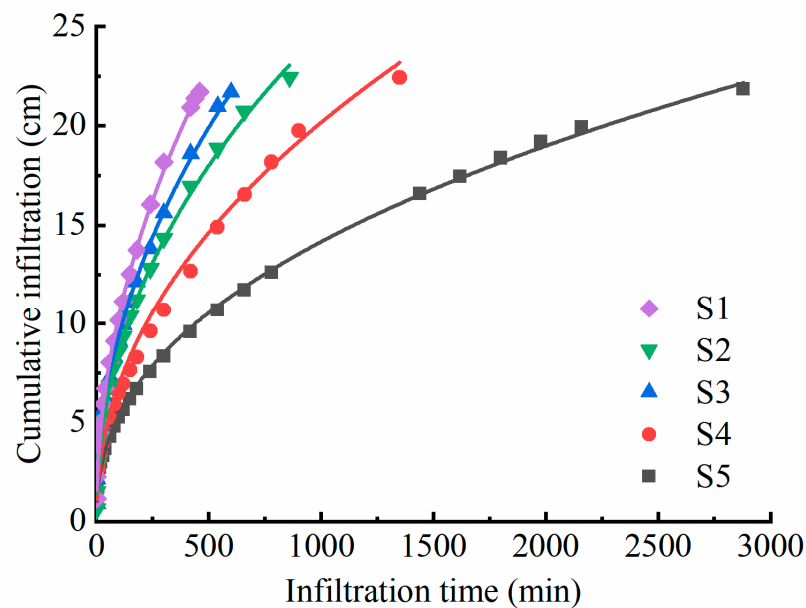


Figure 2. The variation in cumulative infiltration of different soils with infiltration time.

The Kostiakov model was applied to analyze the relationship between cumulative infiltration and infiltration time

$$I(t) = Kt^a \quad (1)$$

where $I(t)$ is cumulative infiltration volume per unit area (cm); t is infiltration duration (min); K is an infiltration coefficient ($\text{cm} \cdot \text{min}^{-a}$); and a is infiltration index. Table 3 shows the fitting results, and the R^2 values are all above 0.99, indicating that the Kostiakov infiltration model can well describe the relationship between cumulative infiltration and infiltration time of soils with different salinity.

Table 3. Fitting parameters of Kostiakov infiltration model.

Soil Number	Soil Number (g/kg)	Kostiakov Model		
		K	a	R^2
S1	18.30	$1.121^a \pm 0.036$	$0.484^a \pm 0.006$	0.999
S2	25.50	$1.045^b \pm 0.041$	$0.458^c \pm 0.007$	0.998
S3	42.20	$1.084^{ab} \pm 0.050$	$0.468^{ac} \pm 0.008$	0.997
S4	79.94	$0.816^c \pm 0.057$	$0.464^b \pm 0.011$	0.993
S5	165.00	$0.760^c \pm 0.026$	$0.423^b \pm 0.005$	0.998

^{a-c} Superscripts with different letters indicate that means are significantly different among forage treatments within each parameter ($p < 0.05$).

As indicated in Table 3, the Kostiakov model's coefficient K and index a decrease with the increase in soil salinity. Specifically, K 's value decreased from 1.121 to 0.760, while parameter a decreased from 0.484 to 0.423. Saline soils S1, S3, S4, and S5 were selected to analyze the relationship between coefficient K and index a in Kostiakov's model and soil salinity change, as shown in Figure 3.

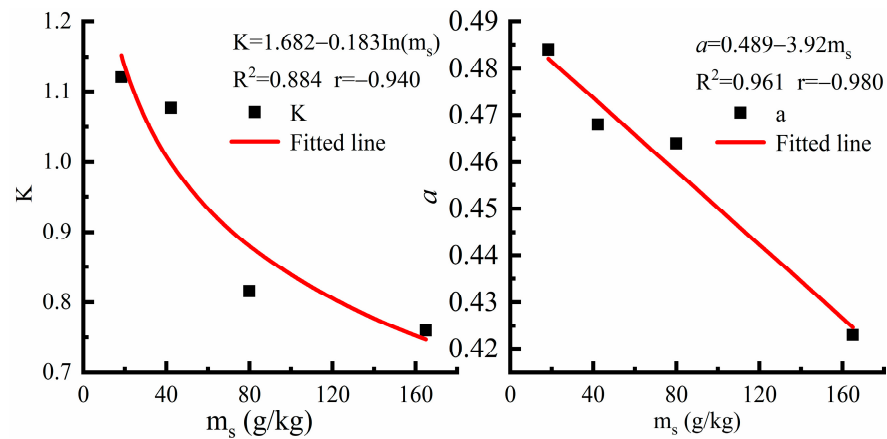


Figure 3. Parameters K and a vary with soil initial salinity. Note: the horizontal coordinate m_s indicates the soil salt content.

After analysis, coefficient K has a linear relationship with the natural logarithm of initial soil salt content, and index a linearly correlates with initial soil salt content. The fitting formulas are as follows, Equation (2) and Equation (3), respectively:

$$K = 1.68 - 0.183 \ln(m_s) \quad (2)$$

$$a = 0.489 - 3.92m_s \quad (3)$$

where represents the initial soil salt content in g/kg.

The fitting coefficients R^2 of Equations (2) and (3) are 0.884 ($p = 0.029 < 0.05$) and 0.961 ($p = 0.002 < 0.05$), respectively, demonstrating a good fitting effect, which indicates that the Kostikov model's parameters K and a for saline soil can be effectively calculated according to initial soil salt content. Incorporating Equations (2) and (3) into Equation (1), the relationship model between cumulative infiltration of saline soil, infiltration time, and soil initial salinity can be obtained, as shown in Equation (4):

$$I(t) = [1.68 - 0.183 \ln(m_s)] t^{0.489 - 3.92m_s} \quad (4)$$

Measured cumulative infiltration of saline soil S2 (salt content 25.5 mg/kg) was selected to verify the modified Kostikov model. The cumulative infiltration of S2 was calculated according to Equation (4) and compared with the measured value. The results are shown in Figure 4.

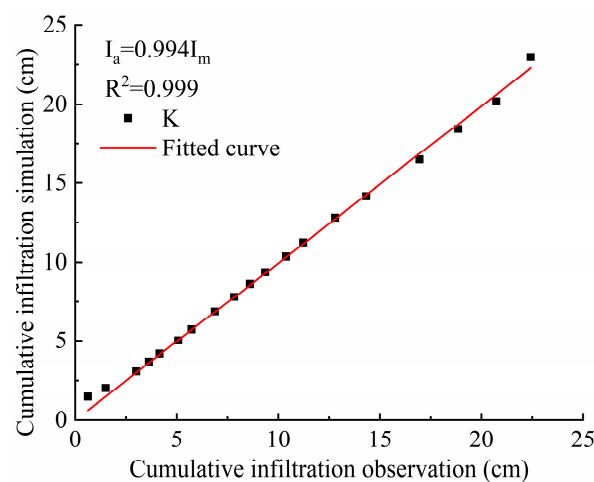


Figure 4. The comparison between measured and simulated values of cumulative infiltration.

In Figure 4, the slope of the fitted curve is 0.994, and R^2 exceeded 0.99. The calculated mean absolute error (MAE) and root mean square error (RMSE) values are 0.20 and 0.33, respectively, and the results are both small. The NSE coefficient is 0.997, demonstrating that the measured cumulative infiltration is in good agreement with the calculated value of the model. Therefore, the modified Kostikov model can well reflect the one-dimensional cumulative infiltration of soils with different salinity over time.

3.1.2. Wetting Front Transport

Wetting front migration is also an important index reflecting soil water infiltration capacity. Figure 5 shows the relationship between the mean wetting front transport distance and time in different saline soils during infiltration. It can be seen from Figure 5 that, in the initial stage of infiltration (about the first 60 min), the transport distance of wetting front in soils with different salinity had little difference. With the passage of time, the wetting front transport distance decreases with soil initial salinity increase. The migration time of different soil wetting front to 45 cm was the shortest (283 min) for S1. S5 required the longest infiltration time (1620 min), while S2, S3, and S4 required 465 min, 363 min, and 615 min, respectively. Correlation analysis showed that soil salt content was significantly correlated with the time required for the wetting front to reach 50 cm ($p = 0.014 < 0.05$), indicating that soil initial salinity had a great influence on the wetting front transport.

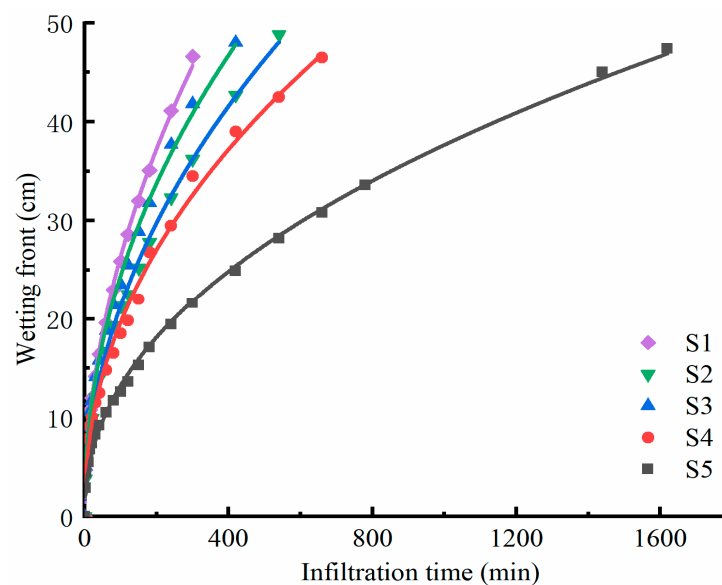


Figure 5. The migration diagram of wetting fronts of different salinization soils.

According to the curve characteristics of the relationship between wetting front transport distance and infiltration time, it is found that the two conform to power function Equation (5), and the fitting results are shown in Table 4.

$$F(t) = At^B \quad (5)$$

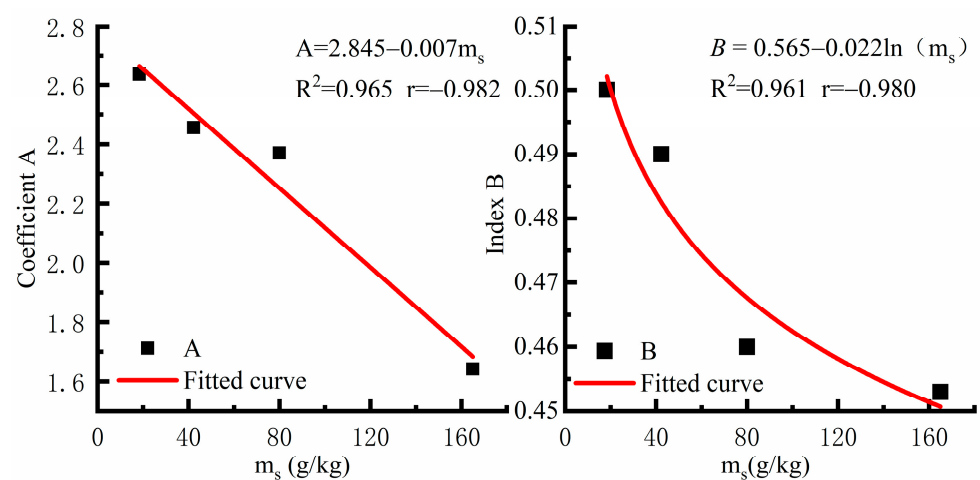
where $F(t)$ is the migration distance of the wetting front, cm; t is the infiltration time, min; A is the fitting coefficient; B is the fitting index.

Table 4. Fitting parameters of wetting front advance of different salinization soils.

Soil Number	Soil Number (g/kg)	$F(t) = At^B$		
		A	B	R ²
S1	18.30	2.636 ^a ± 0.122	0.500 ^a ± 0.009	0.997
S2	25.50	2.534 ^{ab} ± 0.115	0.469 ^b ± 0.008	0.997
S3	42.20	2.456 ^{ab} ± 0.200	0.490 ^a ± 0.016	0.991
S4	79.94	2.371 ^b ± 0.175	0.460 ^{bc} ± 0.013	0.992
S5	165.00	1.642 ^c ± 0.0715	0.453 ^c ± 0.007	0.997

^{a–c} Superscripts with different letters indicate that means are significantly different among forage treatments within each parameter ($p < 0.05$).

Table 4 indicates that the determination coefficient R^2 for fitting different saline soils exceeds 0.99, indicating that Equation (5) can well fit the wetting front migration under one-dimensional vertical infiltration of different saline soils. In Equation (5), both coefficient A and index B decrease with soil salinity increase. Among them, coefficient A has the most obvious change, ranging from 2.636 to 1.642, while index B has a small change, ranging from 0.50 to 0.453, indicating that an increase in soil salinity will hinder the wetting front migration, which is consistent with the results reflected in Figure 5. The changes in parameters A and B in Equation (5) with soil salt content were further analyzed, and the results are shown in Figure 6.

**Figure 6.** Changes in coefficient A and index B under different soil salinization degrees.

As shown in Figure 6, parameter A has a linear relationship with soil salt content, while parameter B linearly correlates with the natural logarithm of soil salt content. Data of saline soils S1, S3, S4, and S5 were selected to establish the relationship between parameters A and B and soil salt content, as shown in Equations (6) and (7).

$$A = 2.845 - 0.007m_s \quad (6)$$

$$B = 0.565 - 0.022\ln(m_s) \quad (7)$$

The R^2 values of both formulas exceed 0.96, indicating a strong fit to the data. For Equation (6), $p = 0.017 < 0.05$, indicating that the model's parameter A is a statistically significant predictor of soil salt content. For Equation (7), $p = 0.097 > 0.05$, the findings indicated no significant difference in the results, potentially due to the constraints of a small sample size [38]. In general, the formula has a good fitting effect on the relationship between parameters A and B and soil salt content. Equations (6) and (7) were put into

Equation (5) to obtain the fitting formula for the wetting front transport distance in saline soil, as presented in Equation (8).

$$F(t) = (2.845 - 0.007m_s)t^{[0.565-0.022\ln(m_s)]} \quad (8)$$

The measured wetting front data of S2 (soil salt content is 25.5 g/kg) were selected to verify Equation (8). The wetting front transport distance in the one-dimensional vertical infiltration process of saline soil S2 was calculated according to Equation (8) and compared with the measured values; the results are shown in Figure 7. Figure 7 shows that the slope of the relationship curve between the measured and calculated values is 1.047. The calculated mean absolute error (MAE) and root mean square error (RMSE) are 1.10 and 1.29, respectively. Moreover, the determination coefficient R^2 is greater than 0.999, indicating that the established fitting formula for the wetting front transport of saline soil (Equation (8)) has high accuracy. Therefore, Equation (8) can be used to deduce the dynamic change process of soil wetting front transport distance and time for different soil salinity.

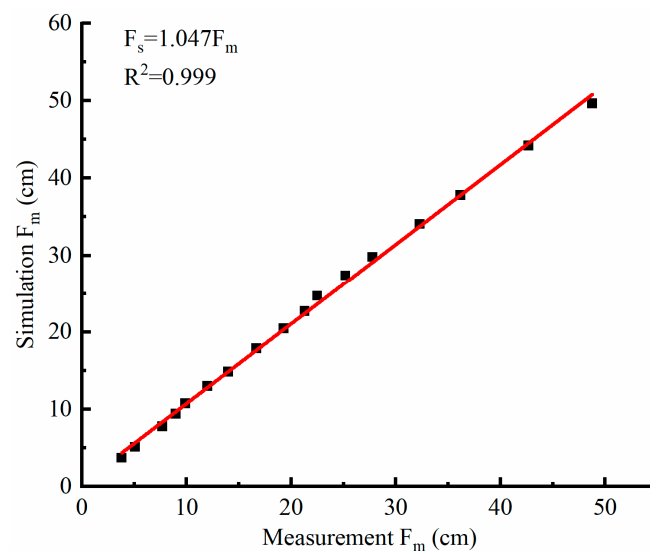


Figure 7. The comparison between the calculated value and the measured value of the wetting front migration.

3.2. Leaching Characteristics

As the actual cumulative infiltration of S1, S3, and S5 was the same at 6.8 L, in order to ensure consistency of data analysis, only the three sets of data were used to analyze the leaching characteristics.

3.2.1. Volume of Leachate

Figure 8 shows the relationship between the cumulative volume of leachates of soils with different salinity and outflow time. In the early stage of leachate at the bottom of the soil column (about 3680 min before), the cumulative leached liquid volume of soils with different salinity showed the same change rule with time, and the cumulative leachate volume increased with an increase in outflow time. After 3680 min, there was no leachate in the S5 soil, which had the highest salinity. The leaching durations of the S1 and S3 soils are approximately 7380 min and 11760 min, respectively. Under the same outflow duration, the total accumulated volume of leachate decreased with an increase in soil initial salinity. Finally, the cumulative leachate volume of S1 was 1500 mL, and the data of S3 and S5 were reduced by 37% and 57.3%, respectively, compared with S1.

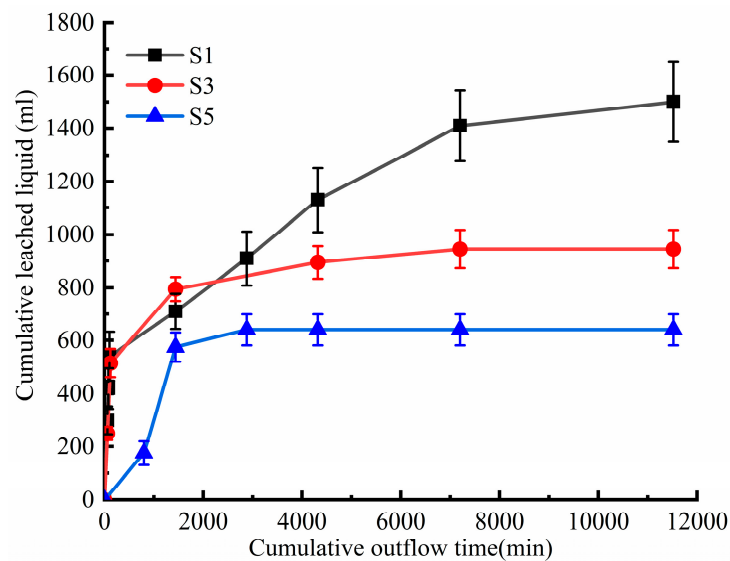


Figure 8. Changes in accumulated leaching liquid volume of different saline soils with time. The error bar represents the standard error value for each sampled event.

3.2.2. Electric Conductivity

Figure 9 shows the relationship between the electrical conductivity of soil leachates of different salinity and outflow time. As can be seen from Figure 9, the change in the leachate conductivity of S1 over time can be roughly divided into three stages. The first stage (0–240 min) was the rapid reduction stage. The second stage (180–3120 min) was a slow reduction stage. The third stage (3120–11,700 min) was basically stable. The leachate conductivity of S3 decreased first and then increased with outflow time, and it reached the lowest in 1620 min after outflow. The electrical conductivity of the S5 leachate increased first and then decreased with outflow time. In general, the electrical conductivity of leachates increased with an increase in soil salinity.

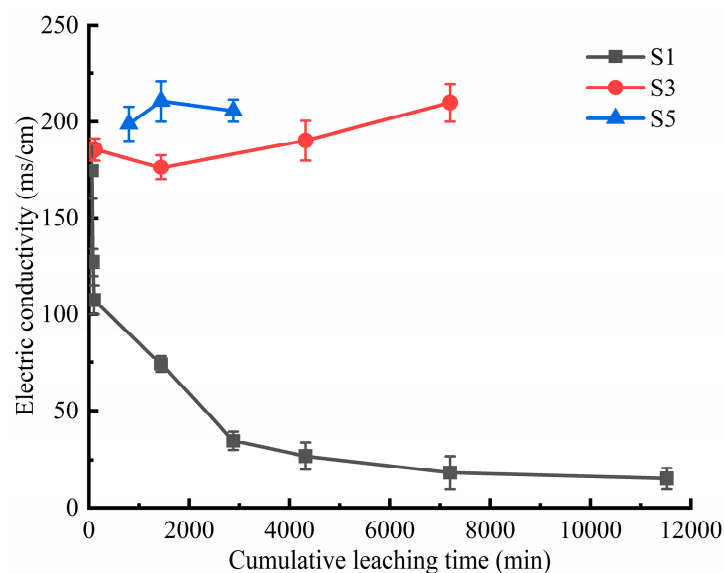


Figure 9. Changes in electric conductivity in leaching solutions of different saline soils with time. The error bar represents the standard error value for each sampled event.

3.2.3. NH_4^+ -N Concentration and NO_3^- -N Concentration

Figure 10 shows the relationship between NH_4^+ -N and NO_3^- -N in soil leachates of different salinity and outflow time. As can be seen from Figure 10, the variation in NH_4^+ -N

in S1 leachate over time can be roughly divided into two stages. The first stage (0–240 min) was the rapid reduction stage. The second stage (240–11,760 min) was the slow reduction stage. The concentration of NH_4^+ -N in the S3 leachate showed a trend of decrease–increase–decrease with the outflow time, and the NH_4^+ -N concentration of leachate in the late stage was higher than that in the early stage. The concentration of NH_4^+ -N in the leachate of S5 increased very slightly over time (from 39.29 to 39.353 mg/L) and was much higher than that of the other two soils. Within 0–3000 min, the concentration of NH_4^+ -N in the leachate of S1 was higher than that of S3, and the rule was the opposite after 3000 min.

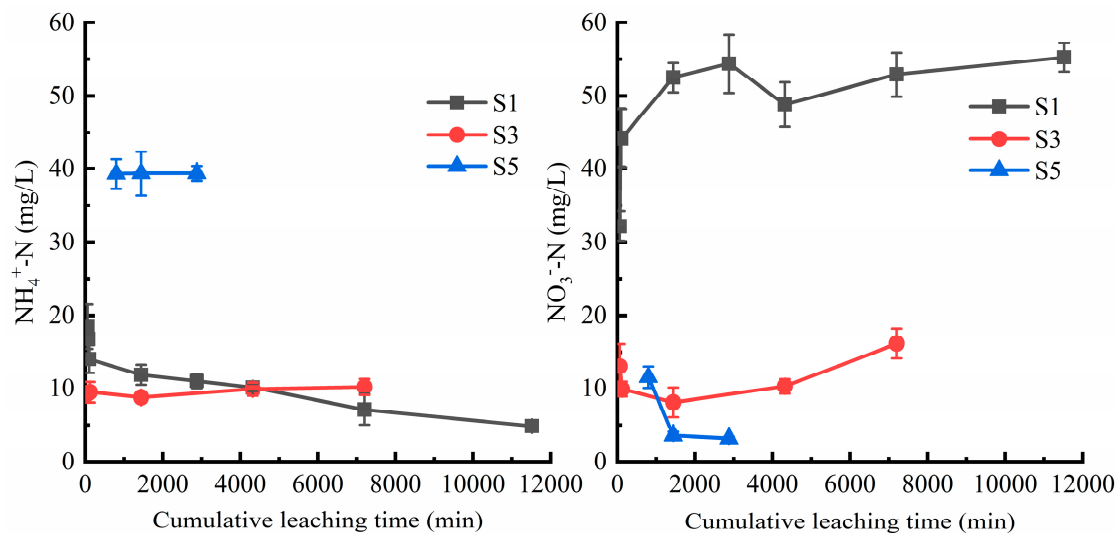


Figure 10. Changes in NH_4^+ -N and NO_3^- -N in leaching solutions of different saline soils with time. The error bar represents the standard error value for each sampled event.

The concentration of NO_3^- -N in S1 leached solution increased with time during the first 3000 min, especially within 0–240 min; the concentration of NO_3^- -N increased very quickly (from 0 to 44.28 mg/L), while the concentration of NO_3^- -N decreased during 3000–4500 min and gradually increased after 4500 min. The concentration of NO_3^- -N in S3 leachate decreased first and then increased, and the concentration of NO_3^- -N in the late stage was higher than that in the early stage, which was similar to NH_4^+ -N in the leachate. Due to the slow transport rate of soil water, a certain volume of leachate was collected at 800 min after outflow, and the concentration of NO_3^- -N in S5 decreased with the increase in time.

4. Discussion

4.1. Effect of Soil Salinity on Infiltration Characteristics

In the initial stage of infiltration, the effects of soil initial salinity on cumulative infiltration and wetting front migration distance were not obvious. This is because, in the early stage of infiltration, the wetting front is near the soil surface (as shown in Figure 2), where the infiltration rate is predominantly influenced by the soil water potential gradient ($\partial h/\partial z$). However, with the prolongation of infiltration time, the cumulative infiltration varied greatly among soils with differing salinity. These differences are primarily attributed to differences in the exchangeable sodium ions of soils with different initial salinity [39]. Previous studies indicate that the hydraulic conductivity properties of soils significantly vary with changes in the content of sodium salts in soil [40]. The increase in soil's exchangeable sodium ions causes a thicker diffuse bilayer and higher electrokinetic potential of soil colloids. Higher electrokinetic potential enhances the dispersion of clay particles and reduces the stability of aggregates [41]. As a result, the large pores and small pores of water movement in soil are destroyed in a relatively short time, thus reducing the hydraulic conductivity of the soil [42]. Additionally, sodium ions in soil can cause large-particle

colloids to disperse into many small-particle colloids, increasing the unit surface area and surface tension (enhancing adsorption), thus slowing soil water infiltration rates [6,43–45]. This phenomenon is reflected in Kostiaikov's infiltration model, in which both the coefficient K and the exponent a decrease with an increase in soil salinity. Previous studies have shown that, the larger the value of K , the higher the initial infiltration rate of soil; the larger the value of a , the larger the slope of the soil infiltration curve, and the faster the instantaneous infiltration rate decay rate. Therefore, coefficient K plays a leading role in the Kostiaikov model at the initial infiltration stage, while index a becomes the main factor affecting the amount of infiltration as the infiltration process progresses [40,46].

Furthermore, coefficient A and exponent B in the power function equation for the wetting front's transport distance versus time also decrease with an increase in soil initial salinity, which is consistent with the conclusions of Han et al. (2020) [40] and Liu et al. (2023) [17]. Although S2 has a lower salt content than S3, it took longer for S2 to reach the same cumulative infiltration and the same wetting front than S3. This could be attributed to S3 having more sand content and lower silt and clay contents than S2 such that, under light salinity, the influence of salt content on water infiltration is less than that of soil particle size.

4.2. Effect of Soil Salinity on Deep Leaching

Leaching is a major contributor to the loss of water, salts, and nutrients from soil, and it also plays a significant role in environmental water body pollution [23]. This study revealed that the volume of leachate decreased as the initial salinity increased. This is because soils with higher initial salinity exhibit slower infiltration rates, resulting in correspondingly slower leaching rates. Generally, leachate conductivity increased with an increase in soil initial salinity, which is closely related to soil water transport rate and initial salinity level. Generally, the electrical conductivity of leachates increases with higher initial salinity, a change closely related to soil water transport rates and initial salinity levels [47]. Soil with low initial salinity has a higher hydraulic conductivity and a faster rate of salt downward transport, leading to salt accumulation primarily in the lower layer. Consequently, the electrical conductivity of leachates from these soils is highest at the initial stage of outflow. As leaching continues, the soil's salt content gradually decreases, leading to a gradual decrease in leachate electrical conductivity over time. For soils with high initial salinity, due to the slow water transport rate, the rate of salt migration and accumulation in the low layers is also slow, leading to peak salt accumulation in the lower soil after a certain period of redistribution. At this time, the electrical conductivity of the bottom leachate peaks, followed by a gradual decrease as soil salt content reduces.

Soil salinity's impact on $\text{NH}_4^+\text{-N}$ in the leachate is primarily linked to the rate of soil moisture transport. In S1 soil, characterized by low initial salinity, the faster water transport rate led to rapid $\text{NH}_4^+\text{-N}$ leaching. Given the absence of external nitrogen sources, the $\text{NH}_4^+\text{-N}$ concentration in the leachate, derived from soil's initial $\text{NH}_4^+\text{-N}$ and mineralization of organic matter, continuously decreased with the extension of the outflow time. For S3 soils with marginally higher initial salinity, there was an increase in $\text{NH}_4^+\text{-N}$ concentration in the leachate during the intermediate stage of outflow. This is because the increase in soil salt reduces the soil's hydraulic conductivity, thereby slowing down the rate of $\text{NH}_4^+\text{-N}$ transport to deep soil. Furthermore, the increase in soil salinity also inhibits mineralization [48,49], leading to the initial $\text{NH}_4^+\text{-N}$ concentration in the leachate primarily from the initial $\text{NH}_4^+\text{-N}$ in the deep soil layer. As time goes by, $\text{NH}_4^+\text{-N}$ transported to lower layers increases and $\text{NH}_4^+\text{-N}$ produced by mineralization increases with the salts leaching out from soil, thus raising the $\text{NH}_4^+\text{-N}$ concentration in the leachate. However, this concentration will eventually decrease in the late stage of outflow due to a lack of external nitrogen sources. In S5 soil with the highest initial salinity, the accumulation of $\text{NH}_4^+\text{-N}$ in the deep soil layer was slow owing to the slow water transport rate, and the mineralization was also slow due to high salinity's inhibitory effect. Consequently, during a short outflow time, the increase in $\text{NH}_4^+\text{-N}$ in the leachate was not obvious. Additionally,

the NH_4^+ -N concentration in S5's leachate was substantially higher than in other soils, likely due to its higher initial NH_4^+ -N content.

In this study, the NO_3^- -N concentrations in the leachates of the three soils followed the order $\text{S1} > \text{S3} > \text{S5}$. This phenomenon is mainly affected by the NO_3^- -N content in the subsoil, which includes both the soil's initial NO_3^- -N content and the NO_3^- -N transported to the subsoil with infiltration water. A greater initial NO_3^- -N content in the soil, coupled with a faster water transport rate, will result in a higher NO_3^- -N concentration in the leachate. Therefore, the NO_3^- -N concentration in the leachate of S1 soil was the highest, while S5, with the lowest initial NO_3^- -N content and slow water transport rate, had the lowest NO_3^- -N concentration in its leachate. After 8000 min, the NO_3^- -N concentration in S5's leachate was marginally higher than that in S3's, possibly due to S5 having higher ammonium nitrogen and organic matter content than S3 (Table 2), both of which can transform into NO_3^- -N. The varying trends in NO_3^- -N concentration in the leachates of different soils over time may be linked to soil salinity. In S1, with lower salinity and faster water transport, the NO_3^- -N concentration in its leaching solution showed an overall increasing trend. The low inflection point in the curve's middle may be related to the decrease in NO_3^- -N generated by soil organic matter mineralization and NH_4^+ -N nitrification during that period. In S3's leachate, the early-stage decrease and later-stage increase in NO_3^- -N concentration were due to increased salinity slowing down the migration rate of NO_3^- -N to the subsoil and intensifying the inhibition of nitrification. Early-stage NO_3^- -N leaching predominantly originated from the soil's initial NO_3^- -N [50]. Later, as NO_3^- -N accumulation in the subsoil increased and soil salt leaching alleviated the inhibition of nitrification, NO_3^- -N leaching also continuously increased. The decreasing trend in NO_3^- -N concentration in S5's leachate is mainly attributed to the slow water transport rate caused by its high salinity. From the concentration of nitrate and nitrogen in the leaching solution, we speculate that the salt in the S5 soil is also less leached. Judging from the concentration of nitrate and nitrogen in the leaching solution, the salt leaching from the S5 soil should also be less. According to our monitoring of the soil salt distribution after infiltration (which is not presented here), this is indeed the case.

5. Conclusions

A Kostiakov model for cumulative infiltration and a power function model for wetting front transport over time were developed and fit the observed data well, quantifying the effects of soil initial salinity. The fitting parameters in the models showed a significant negative correlation with soil salinity. The volume, conductivity, and concentrations of NH_4^+ -N, and NO_3^- -N of the leachate are related to the initial content and water transport rate in soil. In addition, the concentrations of NH_4^+ -N, and NO_3^- -N were also related to the application of exogenous nitrogen fertilizer.

Based on the results of this study, soil with low initial salinity should be supplied with less water and fertilizer appropriately, while soil with high initial salinity needs more irrigation water to meet the requirements of leaching salt. We speculate that nitrogen leaching will increase if the leaching salt requirements are met, so nitrogen fertilizer application strategies need to be considered. For heavy saline soil, deep water drainage should be considered at the same time as salt leaching to prevent deep soil and groundwater pollution. More consideration should be provided to the actual application of nitrogen fertilizer as nitrogen not only migrates with water but also undergoes complex transformations. In the future, many in-depth studies are needed regarding water, salt, and nitrogen of soils with different salinity under the coupled influence of water and fertilizer.

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