



Article Effects of Ionized Water Irrigation on Organic Nitrogen Mineralization in Saline-Alkali Soil in China

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Abstract: The application of ionized water to irrigation, as a new type of water treatment technology, can improve the spatial distribution of water in soil and increase water utilization efficiency, which may affect the microbiological processes involved in nitrogen transformation and alter soil nitrogen supply capability. However, the effects of ionized water technology on soil organic nitrogen mineralization are still in need of further research. In this study, we investigated the soil organic nitrogen mineralization process with four different water additions: non-ionized fresh water (CK), ionized fresh water (DE), non-ionized brackish water (BCK), and ionized brackish water (BDE). By using a short-term laboratory incubation method, we monitored the changes of the inorganic nitrogen concentration in each treatment during the incubation process. We compared the net nitrogen mineralization and nitrogen mineralization rates in different treatments, and fitted the organic nitrogen mineralization process with three models (One-pool model, Special model, and EATM model). We divided the whole incubation process into three periods based on the differences of the organic nitrogen mineralization trends. The results demonstrated that when DE was compared with CK, the net nitrogen mineralization increased by 21.97% and the nitrogen mineralization rate increased by 20.42% in the latter incubation period. When BDE was compared with BCK, the net nitrogen mineralization decreased by 3.63%, and the nitrogen mineralization rate increased by 21.86% in the latter incubation period. When BCK was compared with CK, brackish water irrigation reduced the organic nitrogen mineralization intensity to a certain extent, with the net nitrogen mineralization decreased by 11.62% and the nitrogen mineralization rate decreased by 41.07% in the whole incubation process. When BDE was compared with DE, the net nitrogen mineralization decreased by 30.09% and the nitrogen mineralization rate decreased by 53.39% in the whole incubation process. The simulation model of the soil organic nitrogen mineralization process showed that the special model and EATM model are superior to the One-pool model. This study provides a theoretical basis for the popularization and application of ionized water irrigation in agricultural production.

Keywords: saline-alkali soil; brackish water; ionized water; organic nitrogen mineralization; model fitting

1. Introduction

Ionized water technology was first introduced in the United States and used in industrial water and oil separation treatments [1]. This technology reduces the hydrogen bonding between water molecules, changes the binding structure of water itself, and allows more water molecules to flow into small pores during infiltration [2]. This improves the distribution of soil moisture and increases soil water holding and retention performance [3]. In addition, ionized water irrigation can change the physical and chemical properties of soil [4], which is conducive to improving the effectiveness of soil nutrients and irrigation water use [5]. It has the characteristics of simplicity, low energy consumption, low cost, high efficiency, and environmental protection. Nitrogen, one of the three major nutritional elements which are essential for plant growth, is one of the most abundant mineral elements absorbed by plant roots from soil [6]. Over 95% of the nitrogen in soil is in the form of



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). organic nitrogen which must be converted into inorganic nitrogen through mineralization mediated by soil microorganisms [7,8] that can be absorbed and utilized by plants. The net nitrogen mineralization [9,10] reflects the nitrogen supply capacity of the soil, while the nitrogen mineralization rate reflects the nitrogen supply intensity [11]. Both factors determine the availability of nitrogen for plant growth, development, and microbial assimilation in the soil. Therefore, improving soil organic nitrogen mineralization is of great significance for plant nitrogen utilization and maintaining soil fertility.

Studies have shown the effects of ionized water infiltration on soil physicochemical properties, crop growth, and crop yield [12]. Wang et al. [13] found that ionized brackish water could significantly improve soil water holding efficiency and upper layer salt leaching effects, increasing winter wheat production by a further 46.9%. When the salinity of brackish water was 4 g/L, the net infiltration amount of ionized brackish water increased by 20.5% compared with brackish water [14]. Moreover, Wei et al. [15] demonstrated that compared with non-ionized water, ionized water could improve the desalination effect of the surface (0-20 cm) in the saline-alkali soil. Previous research applied ionized water to irrigating cotton, which resulted in an increase in harvest by 125% [16]. In recent years, the issue of the imbalance between supply and demand of agricultural water resources in China has become increasingly prominent [17,18], particularly in the northwest region where water resources and environmental problems are more severe [19,20]. The soil in the northwest region is primarily sandy loam. Unreasonable irrigation practices can result in increased soil evapotranspiration, excessive salt accumulation, and soil salinization. Li et al. [21] found that saline-alkali soil could cause a 40.0-65.2% increase in net ammonia volatilization, leading to nitrogen loss. Furthermore, a high salt concentration in soil pores could inhibit microbial activity related to organic nitrogen mineralization [22]. Previous studies have mostly focused on the effects of ionized water on soil water, salt transport and crop growth [16,19]. However, there are few reports on the effects of ionized water on soil nitrogen transformation, especially the effects of ionized water irrigation on saline-alkali soil organic nitrogen mineralization.

In order to explore the impact of ionized water on the organic nitrogen mineralization process in saline-alkali soil, we took Xinjiang Uygur Autonomous Region cotton field soil, and using ionized water started a laboratory incubation. We combined an organic nitrogen mineralization model to explore the effects of ionized water (non-ionized water as the control) and ionized brackish water (non-ionized brackish water as the control) on the net nitrogen mineralization and nitrogen mineralization rate in soil samples. In this study, the One-pool model [22], the Special model [23], and the EATM model [24] were used to fit the organic nitrogen mineralization curves of soil samples from each treatment in the experiment, reveal the process of soil nitrogen mineralization, evaluate the capacity of soil nitrogen supply from the model, and then guide the nitrogen nutrient management in agricultural production according to the differences between different treatments. Based on this study, we can further understand the impact mechanisms of ionized water on organic nitrogen mineralization in saline-alkali soil and improve the nitrogen supply intensity of saline-alkali soil. We are hoping to provide a scientific reference for the popularization and application of ionized water irrigation in agricultural production.

2. Materials and Methods

2.1. Soil Sample Collection

The soil sample was collected from the Bazhou irrigation experiment station in the Tarim River basin of the Xinjiang Uygur Autonomous Region in 2021 (86°10′ E, 41°35′ N). The experimental station is located in the Kongque River alluvial plain on the edge of the Tarim Basin, which belongs to a temperate continental desert climate characterized by scarce rainfall and strong evaporation. The mean annual temperature is 11.2 °C, and the mean annual precipitation is 58 mm, mostly concentrated in July and August, with the maximum annual evaporation of 2278.2 mm [25]. The soil sample was taken from the 0–20 cm cultivated layer of cotton field by the five-point sampling method. At each

sampling site, 2 kg soil was collected and fully mixed, totaling 10 kg. The soil bulk density was $1.56 \text{ g}\cdot\text{cm}^{-3}$. The soil particle composition was 4.70% clay, 54.40% silt, and 41.40% sand, indicated that the soil type is sandy loam. The soil pH was 8.7, and the salt composition was mainly sodium chloride with a salt content of $2.21 \text{ g}\cdot\text{kg}^{-1}$, indicating that the soil belonged to mild saline-alkaline soil. The soil total carbon content was $15.7 \text{ g}\cdot\text{kg}^{-1}$ while the soil organic carbon content was $3.4 \text{ g}\cdot\text{kg}^{-1}$. The soil's total nitrogen content was $0.5 \text{ g}\cdot\text{kg}^{-1}$, with a C/N ratio of 6.8. The ammonium nitrogen content was $4.70 \text{ mg}\cdot\text{kg}^{-1}$ and the nitrate nitrogen content was $26.43 \text{ mg}\cdot\text{kg}^{-1}$. The collected fresh soil was thoroughly mixed and air-dried after removing plant roots, grit, and other debris, and finely ground through a 2 mm sieve for subsequent laboratory experiments.

2.2. Experimental Design and Treatments

2.2.1. Ionized Fresh Water Preparation

The preparation system for ionized water included an ionized processor, wires, grounding electrodes, PVC pipes, etc. The electronic processor was produced by South Korea's Yameihua (Beijing) Environmental Technology Development Co., Ltd. (Beijing, China), with a model number of W600DELF. The grounding electrode had a resistance of no more than 5 Ω and was connected to a wire that was inserted into the ground [14,15]. When the water flowed through the electronic processor, the grounding electrode could introduce electrons from the water into the ground, leaving positive ions in the water body, thus making ionized fresh water for subsequent experiments.

2.2.2. Experimental Design and Treatments

In this study, four different treatments were set up, including fresh water irrigation tests and brackish water irrigation tests. Treatments for the fresh water irrigation included non-ionized fresh water (CK) irrigation tests and ionized fresh water (DE) irrigation tests. Treatments for brackish water irrigation included non-ionized brackish water (BCK) irrigation tests and ionized brackish water (BDE) irrigation tests. The fresh water (BCK) irrigation tests and ionized brackish water (BDE) irrigation tests. The fresh water used was tap water with an electrical conductivity (EC) of 187.8 \pm 0.1 μ S/cm. The brackish water used was composed of tap water and sodium chloride reagent, with a salt content of 3 g/L, and an EC of 9.39 \pm 0.01 mS/cm. No significant difference of EC was found between the ionized water and non-ionized water.

Soil samples equivalent to 30.0 g dry soil were placed at the bottom of a 100 mL clear glass flask with a bulk density of $1.56 \text{ g} \cdot \text{cm}^{-3}$. Non-ionized fresh water, ionized fresh water and non-ionized brackish water, and ionized brackish water were used to adjust the soil moisture content to field capacity (θ_{FC}). The initial moisture content of the air-dried soil used in this study was 1.0% in mess, and the soil moisture content of the soil field capacity $(\theta_{\rm FC})$ was 22.7% in mess; therefore, we started the incubation by adding 6.5 mL water in each flask with soil. Incubation flasks were covered with a layer of plastic film to avoid rapid evaporation of the soil moisture, on which several small holes were punctured to ensure ventilation. All of the flasks were cultured in a constant temperature incubator at (30 ± 1) °C protected from light. For the fresh water irrigation test, three repeat samples were taken for each treatment on days 0, 2, 4, 6, 8, 10, 15, 20, 25, and 30 of incubation. For the brackish water irrigation test, three repeat samples were taken for each treatment on days 0, 5, 10, 15, 20, 25, 30, 35, 40, and 45 of incubation. Each of the above samples were quickly frozen in liquid nitrogen and stored in a -80 °C freezer. After the incubation, the concentration of ammonium nitrogen (NH_4^+ -N) and nitrate nitrogen (NO_3^- -N) in the soil samples were uniformly determined.

2.3. Determination of Ammonium Nitrogen and Nitrate Nitrogen Content

Determination of NH_4^+ -N and NO_3^- -N content: Extract the soil samples from each treatment by using a 2 mol/L KCl solution (water to soil ratio of 1:5), shake and extract at 180 r/min for 1 h, centrifuge, filter, take the supernatant, and determine the NH_4^+ -N

and NO₃⁻-N contents in the leachate by using an automatic discrete chemical analyzer (Smartchem 450, AMS Alliance, Rome, Italy) [26].

2.4. Characteristic Indicators of the Organic Nitrogen Mineralization

The soil organic nitrogen mineralization characteristic indicators were calculated as follows:

$$N_m = N_{(NH_4^+ - N)} + N_{(NO_3^- - N)}$$
(1)

$$N_t = N_{mp} - N_m \tag{2}$$

$$V_{\rm Nt} = (N_{\rm mp} - N_{\rm m})/t \tag{3}$$

In Equations (1)–(3), N_m is the inorganic nitrogen content (mg·kg⁻¹); $N_{(NH_4^+-N)}$ is the ammonium nitrogen content (mg·kg⁻¹); $N_{(NO_3^--N)}$ is the nitrate nitrogen content (mg·kg⁻¹); N_t is the net nitrogen mineralization (mg·kg⁻¹); N_{mp} is the inorganic nitrogen content after soil incubation (mg·kg⁻¹); V_{Nt} is the nitrogen mineralization rate (mg·kg⁻¹-d⁻¹); *t* is the incubation time in days (d⁻¹).

2.5. Organic Nitrogen Mineralization Model

The mineralization of soil organic nitrogen follows the principle of first-order reaction kinetics. In this study, the One-pool model, the Special model, and the EATM model were used to simulate the mineralization process of organic nitrogen:

(1) One-pool model [18]:

$$N_t = N_0 \left(1 - \exp(-k_0 t) \right) \tag{4}$$

In Equation (4), N_t is the net nitrogen mineralization (mg·kg⁻¹); N_0 is the nitrogen mineralization potential (mg·kg⁻¹); k_0 is the nitrogen mineralization rate constant in (mg·d⁻¹); and *t* is the incubation time in days (d⁻¹).

(2) Special model [19]:

$$N_t = N_1 \left(1 - \exp(-k_1 t) \right) + C_2 t \tag{5}$$

In Equation (5), N_1 is the nitrogen mineralization potential of the readily mineralizable nitrogen (mg·kg⁻¹); k_1 is the first-order reaction rate (mg·d⁻¹); and C_2 is the mineralization constant of the more stable and less readily mineralizable portion (mg·kg⁻¹·d⁻¹).

(3) EATM model [20]:

$$N_t = K \left[(T - T_0) t \right] n$$
(6)

In Equation (6), N_t is the net nitrogen mineralization (mg·kg⁻¹); T is the incubation temperature (°C); T_0 is the base temperature, which is set at 15 °C; K and n are the characteristic parameters of soil nitrogen mineralization, the K value is the strength of nitrogen mineralization in the early stage of incubation, and the n value is the nitrogen mineralization rate in the later stage of incubation.

2.6. Data Processing

Microsoft Excel v2016 (Microsoft Corp., Redmond, WA, USA) was used to integrate the experimental data. The regression analysis was performed by MATLAB R2017a. Meanwhile, we used a one-way analysis of variance (ANOVA) in SPSS v.25.0 (IBM, Inc., Chicago, IL, USA) to analyze the significance of the difference. Origin2022 (OriginLab Corp., Northampton, MA, USA) was used for graph production. The observed data in this study were the mean values of three repeated samples. The accuracy of the model simulations was evaluated comprehensively by the correlation coefficient (R^2) and root mean square error (RMSE).

3. Results

3.1. Dynamic Characteristics of Organic Nitrogen Mineralization

3.1.1. Characteristics of Soil Organic Nitrogen Mineralization under Fresh Water Irrigation Changes were seen in nitrate, ammonium, and inorganic nitrogen content throughout the incubation period (Figure 1a,b). In order to analyze the characteristics of organic nitrogen mineralization, the whole incubation process (30 d) was divided into three periods: 0–6 d, 6–15 d, and 15–30 d according to the changes of the organic nitrogen mineralization rates. The nitrogen mineralization rates of the CK and DE treatment decreased more rapidly at day 6 and day 15. Before the incubation, the soil nitrate nitrogen content was 26.43 mg/kg and the ammonium nitrogen content was 4.70 mg/kg. At the end of incubation, the content of nitrate and ammonium nitrogen in the CK treatment were 47.03 mg/kg and 3.74 mg/kg, respectively. The content of nitrate and ammonium nitrogen in the DE treatment was 51.45 mg/kg and 3.64 mg/kg, respectively, which showed a growth trend in NO₃⁻-N content during incubation. At the end of incubation, the net nitrogen mineralization amount in the CK treatment was 19.65 mg/kg, while in the DE treatment was 23.96 mg/kg, an increase of 21.97% compared with the CK treatment (*p* < 0.05).



Figure 1. Dynamics of the soil NH_4^+ -N (mg·kg⁻¹), NO_3^- -N (mg·kg⁻¹), and the total inorganic nitrogen (TIN) (mg·kg⁻¹) concentrations under fresh water irrigation treatments during the incubation process. (a) CK: non-ionized fresh water irrigation treatment, (b) DE: ionized fresh water irrigation treatment.

The characteristic indicators of soil organic nitrogen mineralization in the first period were higher than those of the other two incubation periods, and the last period were lower than those of the other two incubation periods (Figure 2) In the first period of incubation (0–6 d), the organic nitrogen mineralization indicators in each treatment was the highest throughout the entire incubation process. During this period, the net nitrogen mineralization amount in the CK and DE treatments were 12.92 mg kg^{-1} and 12.39 mg kg^{-1} . respectively, with a nitrogen mineralization rate of 2.15 mg $kg^{-1} \cdot d^{-1}$ and 2.06 mg $kg^{-1} \cdot d^{-1}$, respectively. There was no significant difference between the two treatments (p > 0.05). In the second period of incubation (6–15 d), the nitrogen mineralization rate of the DE treatment was 54.69% higher than that of the CK treatment, and the net nitrogen mineralization amounts in the CK and DE treatments were 3.29 mg·kg⁻¹ and 7.27 mg·kg⁻¹, respectively. In the third period of incubation (16–30 d), the nitrogen mineralization indicators of the CK treatment were lower than that of the DE treatment, with net nitrogen mineralization amounts of 3.43 mg kg⁻¹ and 4.31 mg kg⁻¹, respectively. When the DE treatment was compared with the CK treatment, the nitrogen mineralization rate increased by 20.42%. Therefore, compared with non-ionized fresh water (CK) treatment irrigation, ionized fresh water (DE) irrigation could increase the net nitrogen mineralization and nitrogen mineralization rate, and increase the intensity of soil organic nitrogen mineralization in the middle and later periods of incubation.



Figure 2. Net nitrogen mineralization of fresh water irrigation treatments in each period. CK: non-ionized fresh water irrigation treatment, DE: ionized fresh water irrigation treatment.

3.1.2. Characteristics of Soil Organic Nitrogen Mineralization under Brackish Water Irrigation

Changes were seen in the nitrate, ammonium, and inorganic nitrogen contents throughout the incubation period (Figure 3a,b). According to the changes of the organic nitrogen mineralization rates, the whole incubation process (45 d) could be divided into three periods: 0–10 d, 11–25 d, and 26–45 d. Before the incubation, soil NO₃⁻-N accounted for 84.89% of the total inorganic nitrogen. At the end of the incubation, soil NO₃⁻-N accounted for 94.10% and 92.14% of the total inorganic nitrogen in the BCK and BDE treatment. There was little change in NH₄⁺-N during incubation. At the end of the incubation period, the amount of net nitrogen mineralization under treatment BCK was 17.36 mg·kg⁻¹, while in treatment BDE it was only 16.75 mg·kg⁻¹, a decrease of 3.64% compared with BCK (p < 0.05).



Figure 3. Dynamics of the soil NH_4^+ -N (mg·kg⁻¹), NO_3^- -N (mg·kg⁻¹), and the total inorganic nitrogen (TIN) (mg·kg⁻¹) concentrations under brackish water irrigation treatments during the incubation process. (**a**) BCK: non-ionized brackish water treatment: (**b**) BDE: ionized brackish water treatment.

In the first period of incubation (0–10 d), the characteristic indicators of soil organic nitrogen mineralization in each treatment was the strongest throughout the whole incubation period (Figure 4). During this period, the net nitrogen mineralization of the BCK and BDE treatments were 11.46 mg·kg⁻¹ and 10.10 mg·kg⁻¹, respectively, with an average nitrogen mineralization rate of $1.15 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$ and $1.01 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$, respectively. The characteristic indicators of soil organic nitrogen mineralization were both higher than those of the other two incubation periods. In the second period of incubation (11–25 d), the mineralization rate of the BDE treatment was 2.68% lower than that of BCK treatment, and the net nitrogen mineralization amount of the BCK treatment was higher than that of the BDE treatment (2.91 mg·kg⁻¹ and 2.83 mg·kg⁻¹, respectively). In the third period of incubation

(26–45 d), the net nitrogen mineralization of the BCK treatment was lower than that of the BDE treatment (2.99 mg·kg⁻¹ and 3.83 mg·kg⁻¹, respectively). Compared with the BCK treatment, the nitrogen mineralization rate increased by 21.86% in the BDE treatment. Therefore, compared with non-ionized brackish water (BCK) treatment irrigation, ionized brackish water (BDE) irrigation could reduce the net nitrogen mineralization, and increase the nitrogen mineralization rate of later periods of incubation.



Figure 4. Net nitrogen mineralization of brackish water irrigation treatments in each period. BCK: ionized water non-ionized brackish water, BDE: ionized brackish water.

3.1.3. Differences in Soil Organic Nitrogen Mineralization under Fresh Water Irrigation and Brackish Water Irrigation

Brackish water irrigation of saline-alkali soil can reduce the intensity of the soil's nitrogen supply to some extent, with the net nitrogen mineralization and nitrogen mineralization rate being significantly lower in the BCK treatment than in the CK treatment; the net nitrogen mineralization and nitrogen mineralization rates were significantly lower in the BDE treatment than in the DE treatment. There was no significant difference in the proportion of inorganic nitrogen generated in each treatment during the three periods of incubation. In the CK treatment, the amount of net nitrogen mineralization in the three periods accounted for 65.78%, 16.76%, and 17.46%, respectively (Figure 2). In the DE treatment, the amount of net nitrogen mineralization in the three periods accounted for 51.69%, 30.33%, and 17.98%, respectively (Figure 2). In the BCK treatment, the amount of net nitrogen mineralization in the three periods accounted for 66.02%, 16.75%, and 17.23%, respectively (Figure 4). In the BDE treatment, the amount of net nitrogen mineralization in the three periods accounted for 60.24%, 16.91%, and 22.85%, respectively (Figure 4).

3.2. Comparison and Analysis of Three Organic Nitrogen Mineralization Models

Applying the soil organic nitrogen mineralization model to simulate soil mineralized nitrogen could not only reveal the process of soil nitrogen mineralization, but also evaluate the capacity of the nitrogen supply. In this study, the One-pool model, Special model, EATM model were used to evaluate the capacity of nitrogen supply, as shown in Table 1 and Figure 5.

Table 1. Fitting accuracy of soil organic nitrogen mineralization models under different treatments.

Treatments	One-Pool		Sp	ecial	EATM	
	<i>R</i> ²	RMSE	R^2	RMSE	<i>R</i> ²	RMSE
СК	0.992	1.514	0.999	0.416	0.999	0.154
DE	0.998	0.799	0.999	0.441	0.999	0.796
BCK	0.996	1.161	0.999	0.382	0.999	0.399
BDE	0.996	1.330	0.999	0.434	0.999	0.491

Note: CK: non-ionized fresh water, DE: ionized fresh water, BCK: ionized water non-ionized brackish water, BDE: ionized brackish water.



Figure 5. Fit curves of soil organic nitrogen mineralization in different treatments. (**a**) CK: non-ionized fresh water, (**b**) DE: ionized fresh water, (**c**) BCK: ionized water non-ionized brackish water, (**d**) BDE: ionized brackish water.

It could be seen that the fitting effects of all three models could reach a significant level ($R^2 > 0.99$). The RMSE (root mean squared error) showed that the Special model and the EATM model were better fitted than the One-pool model. In the One-pool model, the N_0 was the nitrogen mineralization potential, which represented the maximum amount of organic nitrogen in the soil that could generate inorganic nitrogen, and k_0 was the rate constant of organic nitrogen mineralization. From Table 2, it could be seen that the N_0 of the DE treatment was significantly higher than that of CK (p < 0.05), an increase of 26.68%. However, the N_0 of BCK treatment was close to BDE treatment. In the Special model, the N_1 of CK and DE were greater than the N_1 for BCK and BDE. The C_2 of CK and DE were greater than C_2 for BCK and BDE. The N_1 of BCK is the highest, while the N_1 of BDE is the lowest. For the EATM model, the nitrogen mineralization rate of the fresh water treatment in the early stage was significantly higher than the brackish water treatment. The DE treatment increased the nitrogen mineralization rate by 42.07% compared with the CK treatment in the later stage. The BDE treatment in the later stage.

Table 2. Effects of different treatments on soil organic nitrogen mineralization model parameters.

	One-Pool		Special			EATM	
Treatments	N ₀	k_0	N_1	k_1	<i>C</i> ₂	K	п
	(mg·kg ⁻¹)	(d-1)	(mg·kg ⁻¹)	(d-1)	(mg·kg ⁻¹ ·d ⁻¹)		
СК	19.266	0.183	12.002	0.531	0.268	3.768	0.271
DE	24.407	0.124	16.856	0.198	0.242	2.350	0.385
BCK	17.618	0.091	9.592	0.307	0.183	2.001	0.333
BDE	17.599	0.076	7.852	0.408	0.211	1.447	0.377

Note: CK: non-ionized fresh water, DE: ionized fresh water. BCK: ionized water non-ionized brackish water. BDE: ionized brackish water.

4. Discussion

4.1. The Effects of Ionized Water on Organic Nitrogen Mineralization in Saline-Alkali Soil

The net nitrogen mineralization was low in this study (16.75–23.96 mg/kg), and similar to the nitrogen mineralization cultivation experiment results of Li et al. [27] in low fertility soil (10.64–22.80 mg/kg). This study found the DE treatment significantly promoted the generation of inorganic nitrogen through the entire incubation period compared with the CK treatment irrigation. It can be seen that irrigation with ionized water can significantly improve the nitrogen supply capacity of saline-alkali soil and make its nitrogen supply more sustainable. The process of soil organic nitrogen mineralization was significantly inhibited under the conditions of ionized brackish water (BDE) irrigation, which might be due to the high concentration of salt in the irrigation water inhibiting organic nitrogen mineralization.

In the first period of incubation, there was no significant difference (p > 0.05) in the characteristic indicators of soil organic nitrogen mineralization between each two treatments (CK and DE, BCK and BDE), which might be due to the dry soil effect. The process of dry soil effect led to the death of some microorganisms and subsequently releasing the nutrients in the body [28], resulting in an increase in the nutrients that could be utilized by microorganisms in the soil. These factors resulted in the proliferation and growth of microorganisms after the air drying soil was cultured with water [29], and the soil organic nitrogen mineralization intensity was significantly improved [30], thus quickening the mineralization and decomposition of organic nitrogen in soil [31]. Therefore, the differences between the four treatments in this study could not be solely reflected by the organic nitrogen mineralization characteristic indicators in the first period of incubation.

Under the conditions of fresh water irrigation, the controllable factors of soil temperature, water content, salinity, etc. remained constant during the whole incubation period. Therefore, it was speculated that the main ways that ionized water irrigation affects soil organic nitrogen mineralization are as follows. Firstly, ionized water can reduce the viscosity and surface tension of water, bind water molecules into clusters, reduce the contact angle, and improve the permeability and diffusion performance of water [2]. Water can more easily penetrate into smaller soil pores, promoting the dissolution and transport of mineral elements in the soil, and the ionized water dissolves the nutrients present in the fine pores of the soil, thus increasing the substrate content available for organic nitrogen mineralization thereby reducing the soil salinity [32,33], enhancing the functional activity of microbial enzymes related to nitrogen mineralization in the soil [34], and increasing net nitrogen mineralization and nitrogen mineralization rate. Secondly, the dissolved oxygen content in the soil increased significantly after the irrigation with ionized water [14], which can better meet the need for growth and reproduction of aerobic microorganisms, and further promote the mineralization and decomposition of organic nitrogen and the nitrogen cycle process [18]. Thirdly, the composition and stability of soil aggregates can also affect the supply of available nutrients in the soil. Research conducted by Wang et al. [2] pointed out that ionized water can promote the formation of soil aggregates, and the proportion of different sized aggregates can affect the enzymatic activity in the soil. Aggregates of appropriate sizes can enhance the strength of microbial mineralization.

Previous studies have shown that a high salt concentration in soil pores can significantly inhibit microbial activity and reduce microbial biomass [18,35]. The brackish water contained a total dissolved solid (TDS) of 3 g/L. After ionized water treatment, the infiltration capacity of irrigation water was enhanced [2], and more brackish water dissolved more salt in the soil, resulting in an increase of the total dissolved solid, causing more salt to flow into smaller soil pores, inhibiting the growth of microorganisms, thus further reducing soil mineralization intensity. Based on field experiments, Wei et al. [15] showed that ionized brackish water irrigation could reduce soil salinity, improve soil environment, and promote crop growth. This was because under field conditions, the ionized brackish water can leach more salts out of the root zone and stimulate the microbial activity in the rhizosphere. Therefore, when applying ionized brackish water irrigation, we should pay attention to farmland drainage to ensure the availability of good infiltration conditions in the field.

4.2. Evaluation of Organic Nitrogen Mineralization Model

When the One-pool model is used to predict organic nitrogen mineralization, the maximum soil organic nitrogen mineralization capacity (N_0) can be calculated according to the soil net nitrogen mineralization amount (N_t) [18]. Theoretically, the N_0 should be greater than the measured N_t . Combined with the fitting results of this study, the N_t of DE treatment, BCK treatment, and BDE treatment were 98.23%, 98.55%, and 95.20% of N_0 , respectively, but the N_t of the CK treatment was 1.97% higher than the N_0 . This might be due to the error of the One-pool model on the nitrogen supply intensity (k_0) of the whole process during the dry soil effect period, indicating that the One-pool model had a certain limitation.

The Special model can more intuitively describe the nitrogen content of the easily mineralized part and the hard-mineralized part of the soil, and predict the mineralization rate of organic nitrogen more accurately [19]. The nitrogen content of the easily mineralized part (N_1) was lower than the nitrogen mineralization potential (N_0) predicted by the One-pool model, while the value of k_1 was significantly higher than the mineralization rate constant (k_0) predicted by the One-pool model, because the content of easily mineralized nitrogen was smaller than the total nitrogen content of soil and had a higher mineralization rate than the latter. The N_1 and C_2 values of CK and DE are higher than those of BCK and BDE, indicating that brackish water irrigation may reduce the amount of organic nitrogen mineralization to a certain extent compared with freshwater irrigation, which is consistent with the results of the One-pool model. In terms of its fitting effect, the Special model is superior to the One-pool model.

The EATM model divided the experiment into early stage and late stage. The model analyzed the trend of organic nitrogen mineralization from the perspective of the incubation stage. The *K* value showed the nitrogen mineralization rate of fresh water treatment as higher than the brackish water treatment. In the early stage, the *n* value of DE is greater than CK, and the *n* value of BDE is greater than BCK, which indicates that the ionized water treatment can make the nitrogen supply of soil last longer in the later stage, and then it may provide more inorganic nitrogen for crop growth and improve crop yield through the use of ionized water irrigation. However, this model was an empirical model that reflected only the relationship between an effective incubation temperature above 15 °C and organic nitrogen mineralization. The model could not reflect the characteristics of organic nitrogen mineralization when the incubation temperature was lower than the base temperature [20]. This study showed that the ETAM model, based on a constant temperature of 30 °C short-term incubation experiment, had a high degree of model fitting.

5. Conclusions

This study compared and analyzed the effects of adding CK and ionized fresh water (DE), non-ionized brackish water (BCK), and ionized brackish water (BDE) to soil organic nitrogen mineralization in saline-alkali soil in Xinjiang, China. The main conclusions were as follows: First, under the conditions of fresh water irrigation, ionized water improved the intensity of soil organic nitrogen mineralization; under the conditions of brackish water irrigation, the ionized water could inhibit the intensity of soil organic nitrogen mineralization to some extent. Second, compared with fresh water irrigation, brackish water irrigation had an inhibitory effect on the intensity of organic nitrogen mineralization, and ionized brackish water. Therefore, the use of ionized water irrigation in well-structured soil can improve the nitrogen supply capacity of the soil, and accelerate the leaching out of soil salt from the root zone. However, when using ionized water for irrigation on poorly-structured soil with a low percolation intensity, drainage in time is needed to reduce the negative effects of salt concentration. Third, the EATM model

and Special model were a better fit than the One-pool model, but due to the different physical meanings of each model parameter, they can be reasonably selected for different research purposes. This study could provide a theoretical basis for the popularization and application of ionized water irrigation in agricultural production.

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