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RESEARCH ARTICLE

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Optimum combination of soil amendments under drip irrigation with different water sources in coastal areas of East China

Yahui Liu[1], Shumei Zhou[2], Jianping Sun[1], Xiuping Wang[1] and Zaijian Yuan[3]

[1]Institute of Coastal Agriculture, Hebei Acad. Agr. For. Sci., Center for Saline and Alkali Land Green. Eng. Technol. of Hebei Province, Key Laboratory of Plant Salt Tolerance Research of Tangshan City, Caofeidian 063299, China. [2]School of Management and Economics, Hebei Univ. of Sci. & Technol., Center for Ecol. Econ. & Sust. Devel. of Hebei Province, Shijiazhuang 050018, China. [3]Guangdong Key Laboratory of Integrated Agro-environmental Pollution Control and Management, Guangdong Inst. of Ecoenviron. Sci. & Technol., Guangzhou 510650, China.

Yahui Liu and Shumei Zhou contributed equally to this work

Abstract

The effects of drip irrigation (DI) with fresh water (FW) and brackish water (BW) on saline-alkali soil improvement were compared under treatments of five amendment combinations. The experiment was designed using the orthogonal test method and performed using an indoor DI system. Soil electrical conductivity (EC), pH, sodium adsorption ratio and soil nutrients were analyzed after DI both before evaporation and after one month of evaporation. The results showed that after one month of evaporation, soil EC increased by an average of 97.26% and 27.76% for the FW and BW treatments, respectively. Furthermore, it was shown that soil nutrients increased greatly under the BW treatment and that cow dung proved to be a leading agent influencing soil nutrients except available soil potassium (p<0.05). Consequently, the optimum combination of soil amendments was determined as 0.03 m^3/m^2 of straw, 3 kg/m^2 of phosphogypsum, 0.04 m^3/m^2 of cow dung, 0.6 kg/m^2 of humic acid and 0.18 kg/m^2 of microbial fertilizer under the BW treatment.

Additional keywords: saline-alkali soil; orthogonal test; fresh water; brackish water; soil improvement.

Abbreviations used: BW (brackish water); DI (drip irrigation); EC (electrical conductivity); FW (fresh water); OM (organic matter); SAR (sodium adsorption ratio); ANOVA (analysis of variance).

Authors' contributions: Conceived, designed and performed the experiments: XW, YL, and JS. Analyzed the data: SZ and YL. Wrote the paper: SZ, YL and ZY. All authors read and approved the final manuscript.

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Correspondence should be addressed to Xiuping Wang: wxp1593215@163.com, or Zaijian Yuan: selfsurpass@163.com (shared corresponding authors).

Introduction

Saline soils are important land resources that are widely distributed throughout China. As an important subclass of saline soils, the coastal saline soil area is approximately 7% of the total area of saline soils, and mainly distributed in East China. The reclamation of these saline soils is essential for the sustainable development of agriculture and is important to underpin crop production in coastal regions (Rengasamy, 2006; Weng *et al.*, 2010; Mao *et al.*, 2016).

Various techniques have been applied to reclaim coastal saline soils and enhance soil fertility and crop yield, including improvement measures in engineering, chemistry, biology and physics (Qadir *et al.*, 1996; Xiong *et al.*, 2012; Luo *et al.*, 2015; Gupta *et al.*, 2016; Mao *et al.*, 2016). Amelioration of saline soils with amendments is an established technology. Over time, gypsum, cow dung, humic acids, crop straw and microbial fertilizer have been used for soil reclamation. Gypsum adds Ca^{2+} to saline soils and decreases exchangeable sodium (Kelly & Brown, 1934) and can also improve other properties such as soil aggregate structure, soil bulk density, soil permeability and alkalization (Clark & Baligar, 2003). Applying cow dung can effectively improve soil fertility, enhance the activity of soil microorganisms, and promote crop growth (Liu L *et al.*, 2015; Liu Y *et al.*, 2015). Humic acids contain large amounts of active groups and great cation exchange capacity: they reduce soil pH and alkalinity by neutralization reaction and ion exchange interactions (Tong *et al.*, 2014). With crop straw returned to soil, soil structure and properties including water content, fertilizer, gas and heat condition of soils are improved (Lu *et al.*, 2016). Microbial fertilizer contains large amounts of beneficial microorganisms and organic matter (OM), which produce large amounts of organic acids during the decomposition process. Microbial fertilizer can effectively improve the physical and chemical properties of saline soils, increase microbial activity and therefore enhance soil fertility (Gu, 2013). These amendments can effectively improve the physical and chemical qualities of saline soils. However, soil reclamation with amendments would require more time without additional measures such as leaching (Liu L *et al.*, 2015).

The leaching method is one of the most important techniques and has been widely used to reclaim saline soils (Shainberg *et al.*, 1991; Chaganti *et al.*, 2015). However, the traditional leaching (continuous or partial ponding) method is limited in coastal regions due to shortages of high quality water. Drip irrigation (DI) is an effective irrigation technique for improving water use efficiency and has been successfully applied in reclamation of saline soils. In addition, DI is regarded as the most promising irrigation system for use with saline (brackish) water, which is readily acquired in coastal regions and can be used as an alternative to freshwater (Li X *et al.*, 2015). Drip irrigation applies water precisely and uniformly at high frequencies and maintains high soil matric potential in the root zone; thus, DI compensates for the decreased osmotic potential caused by irrigation with saline water and enables the maintenance of constant high total water potential for crop growth (Li X *et al.*, 2015).

As an important land reserve, coastal saline areas of East China play a key role in releasing the tense situation of limited farmland resources, which has imposed a great pressure on sustainable food production for China's booming population. Extensive research has been conducted over decades with respect to using either soil amendments or the DI method to reclaim saline-sodic soils; however, combining effects of soil amendments with DI are questionable and warrant further study.

In the present study, the effects of coapplication of straw, phosphogypsum, cow dung, humic acid, and microbial fertilizer on coastal saline soil improvements were investigated under DI with two kinds of water sources including fresh water (FW) and brackish water (BW). The study aimed to determine 1) the best water source for DI, and 2) the optimum combination of soil amendments to improve coastal saline soils. The results could elucidate the approach to improving saline-alkali soils where subsurface pipes are laid to discharge salt in the coastal field.

Material and methods

Soil sample collection and soil properties

Soils were taken from uncultivated saline-alkali land (117°38′26″E, 38°27′40″N) near the coast of Bohai District in Cangzhou City, Hebei Province, China (Fig. 1). The area experiences a warm temperate semi humid monsoon climate. The annual mean precipitation is approximately 600 mm, 70-80% of which occurs from July to August. Experimental soils were clayey coastal saline soils, collected from the depth range of 0-100 cm, mixed, air dried and sieved (2-mm mesh). The contents

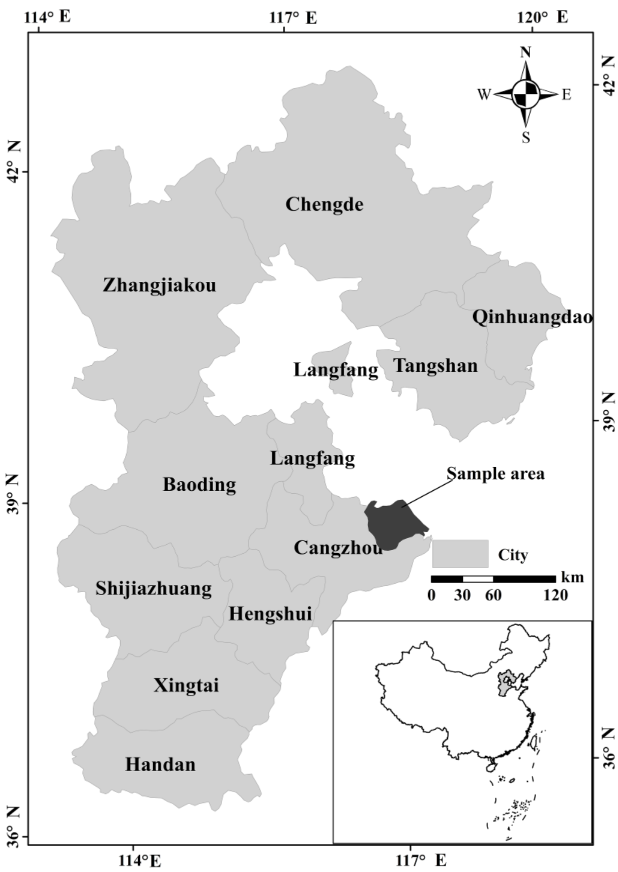

Figure 1. Location of sample area in Cangzhou city, Hebei Province. Experimental soils and brackish water were both taken from this area.

of Na^+ and Cl^- in the test soils accounted for 32.3% and 45.3% of the total ion content, respectively. Therefore, the soil salinity mainly consisted of NaCl. The experimental soils exhibited an electrical conductivity EC= 8.02 dS/m, pH= 8.69 and sodium adsorption ratio SAR= 40.6 $(mmol/L)^{0.5}$. Soil OM, available nitrogen (N), available phosphorus (P) and available potassium (K) were 25.3 g/kg, 36.7 mg/kg, 11.7 mg/kg and 691.0 mg/kg, respectively. Soil bulk density was 1.75 g/cm^3, and soil aggregates with diameters less than 0.5 mm accounted for 97.22% of the total soil mass. The soil chemical properties are shown in Table 1.

Experimental materials

The experiments were conducted at the Institute of Coastal Agriculture, Hebei Academy of Agriculture and Forestry Sciences in Tangshan City, Hebei Province, China. Soil amendments included straw (A), phosphogypsum (B), cow dung (C), humic acid (D) and microbial fertilizer (E). The contents and sources for soil amendments are shown in Table 2.

Experimental design

Orthogonal testing design is an optimization method for studying experiments with multiple factors and multiple levels. Certain representative points are selected for testing based on orthogonal tests instead of conducting every test (Wang & Wang, 2012). This method is an efficient, fast and economical experimental design method, and has been widely used in many fields. In this study, orthogonal testing was performed in order to obtain the best combination of the soil amendments. Table 3 shows the orthogonal design [L16 (4^5) for five soil amendments (labeled from A to E) at four levels (labeled from 1 to 4, followed by the corresponding doses)] in this study: straw (0.01, 0.02, 0.03 and 0.04 m^3/m^2 for A1, A2, A3 and A4, respectively), phosphogypsum (1.5, 3, 4.5 and 6 kg/m^2 for B1, B2, B3 and B4, respectively), cow dung (0.01, 0.02, 0.03 and 0.04 m^3/m^2 for C1, C2, C3 and C4, respectively), humic acid (0.3, 0.6, 0.9 and 1.2 kg/m^2 for D1, D2, D3 and D4, respectively), and microbial fertilizer (0.045, 0.09, 0.135 and 0.18 kg/m^2 for E1, E2, E3 and E4, respectively) which were optimized according to the practice of a previous demonstration project for improvement of saline-alkali soils in the study area (Liu Y *et al.*, 2015). The experiment was set up with three replicates. The simple average values of the three replicates of each treatment were deemed the experimental index values.

In this study, two varieties of irrigation water sources were used, viz. fresh water (tap water) with salinity of 1.4 g/L from the local 200 m-deep well and brackish water with salinity of 3.5 g/L from a 500 m-deep well in the sample area of Xinhai Biotechnol.

Table 1. Soil chemical properties in the experiment.

Soils	EC (dS/m)	pH	SAR $(mmol/L)^{0.5}$	Cation mass fraction (mmol/L)				Anion mass fraction (mmol/L)			
				Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}
Original	8.02	8.69	40.6	55.0	5.2	0.9	0.9	2.8	0	51.5	4.8
FW	0.5-1.8	7.9-8.5	2.7-11.3	4.5-10.8	0.3-1.2	0.2-1.9	0.2-0.9	1.0-3.0	0	2.5-4.0	8.5-34.7
BW	0.8-3.9	7.6-8.3	6.1-11.7	7.3-16.7	0.5-1.2	0.4-2.0	0.4-0.8	2.5-6.0	0	7.5-26.3	0.9-5.8

FW, BW: soils amended with fresh water and brackish water after one-month evaporation, respectively. EC: soil electrical conductivity. SAR: sodium adsorption ratio.

Table 2. Properties and sources of soil amendments in the experiment.

Soil amendments	Main properties and content	Source
A-Straw	1-2 cm in length, contents of OM, available N, P, K: 93%, 0.5%, 0.1% and 1.1%	A farm near the experimental site
B-Phosphogypsum	$CaSO_4 \cdot 2H_2O$, water content: 20%, Ca and P: 2.1% and 1.6%	Phosphate fertilizer plant of Zhengding County, Hebei Province
C-Cow dung	Contents of OM, available N, P, K: 14.5%, 0.4%, 0.2% and 0.1%	A farm near the experimental site
D-Humic acid	Content of OM stem base: 56%; humic acid dry basis: 38%; ash content: 25.6%	Inner Mongolia Simon Industry & Trade Group Company Limited
E-Microbial fertilizer	Trichoderma with living spore content no less than 2×10^8 g^{-1}.	Biology Institute of Shandong Academy of Sciences

OM: organic matter.

Table 3. Levels and the corresponding doses (inside the brackets) for orthogonal experimental design for soil amendments.

Treatments	Straw (A, m^3/m^2)	Phosphogypsum (B, kg/m^2)	Cow dung (C, m^3/m^2)	Humic acid (D, kg/m^2)	Microbial fertilizer (E, kg/m^2)
T1	A1(0.01)	B1(1.5)	C1(0.01)	D1(0.3)	E1(0.045)
T2	A1(0.01)	B2(3.0)	C2(0.02)	D2(0.6)	E2(0.090)
T3	A1(0.01)	B3(4.5)	C3(0.03)	D3(0.9)	E3(0.135)
T4	A1(0.01)	B4(6.0)	C4(0.04)	D4(1.2)	E4(0.180)
T5	A2(0.02)	B1(1.5)	C2(0.02)	D3(0.9)	E4(0.180)
T6	A2(0.02)	B2(3.0)	C1(0.01)	D4(1.2)	E3(0.135)
T7	A2(0.02)	B3(4.5)	C4(0.04)	D1(0.3)	E2(0.090)
T8	A2(0.02)	B4(6.0)	C3(0.03)	D2(0.6)	E1(0.045)
T9	A3(0.03)	B1(1.5)	C3(0.03)	D4(1.2)	E2(0.090)
T10	A3(0.03)	B2(3.0)	C4(0.04)	D3(0.9)	E1(0.045)
T11	A3(0.03)	B3(4.5)	C1(0.01)	D2(0.6)	E4(0.180)
T12	A3(0.03)	B4(6.0)	C2(0.02)	D1(0.3)	E3(0.135)
T13	A4(0.04)	B1(1.5)	C4(0.04)	D2(0.6)	E3(0.135)
T14	A4(0.04)	B2(3.0)	C3(0.03)	D1(0.3)	E4(0.180)
T15	A4(0.04)	B3(4.5)	C2(0.02)	D4(1.2)	E1(0.045)
T16	A4(0.04)	B4(6.0)	C1(0.01)	D3(0.9)	E2(0.090)
Control (CK)	(0)	(0)	(0)	(0)	(0)

Table 4. Properties of different water sources in the experiment.

Water source	EC (dS/m)	SAR $(mmol/L)^{0.5}$	Cation mass fraction (mmol/L)				Anion mass fraction (mmol/L)			
			Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}
FW	2.3	8.8	16.3	0.1	1.8	1.6	6.5	0	16.1	0.3
BW	5.8	13.3	39.5	0.3	3.6	5.2	4.6	0	50.3	1.3

FW, BW: soils amended with fresh water and brackish water after one-month evaporation, respectively. EC: soil electrical conductivity. SAR: sodium adsorption ratio.

Co. Ltd. at Nanpai River Town in Cangzhou City, Hebei Province (Fig. 1). The properties of water sources used are shown in Table 4. The ID water supply system was performed with a Markov bottle (Fig. 2). The Markov bottle is a constant flow water supply device and has been extensively used in infiltration evaporators and experimental water supply systems. It controls the constant water supply flow by adjusting the height difference between the Markov bottle inlet and the water supply pipe outlet. In this study, a Markov bottle with an internal diameter of 14 cm and a height of 80 cm was employed. During the process of DI, the water level in the soil column moves downwards, causing the pressure difference between the Markov bottle and the soil column, which forces the Markov bottle to fill the soil column through the water hose. Therefore, the height of the water surface in the Markov bottle decreases, and the amount of DI is measured by the decrease in the height of the Markov water surface. Test soils, which were well-mixed with amendments at required doses according to the experimental design, were filled in an organic glass column with different heights due to implementation of soil amendments. The glass column was 0.1 cm thick, 100 cm tall and 15 cm in diameter (Liu Y *et al.*, 2015). Gravels with a median diameter of approximately 4 cm were laid in the bottom of the soil column as a leaching layer with thickness of 5 cm. Using a DI system with a flow rate of 1.38 L/h under a 10 m DI tape, 5 L of water was used for DI for each soil column with a drop rate of 0.5 L/h, according to the former study results of our group as well as the situation of the testing area (Liu Y *et al.*, 2015). The DI process lasted for approximately 3 days. Soil columns were evaporated for 30 days under a shelter outdoors after irrigation to test soil salinization.

Analytical methods

The topsoil (0-20 cm) is deemed the most important portion for agricultural production and is directly

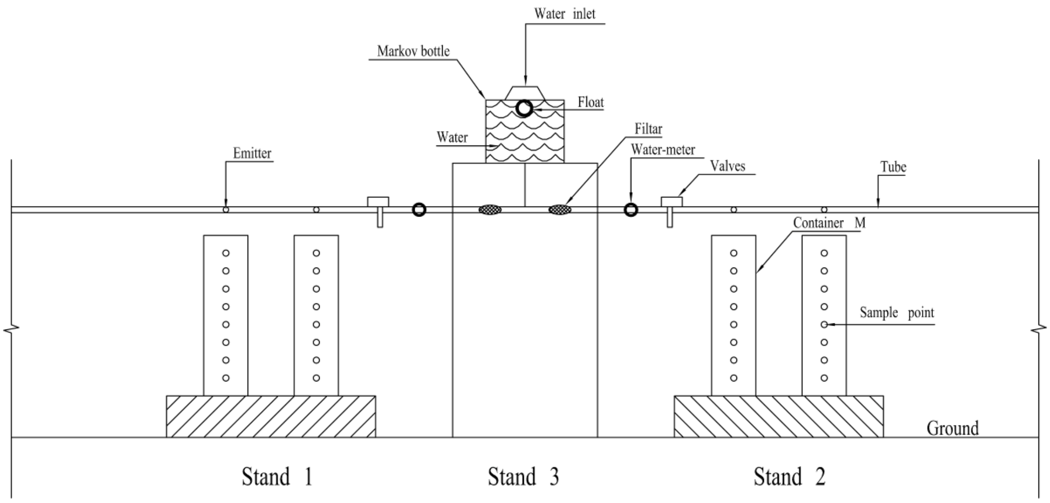

Figure 2. Experimental drip irrigation frame. Stand 1 and Stand 2 represent 8 treatments of either kind of water resource (fresh water (FW) or brackish water (BW)) respectively for one set of drip irrigation experiment. Stand 3 represents the water supply system using a Markov bottle device.

related to a stable and high yield of food production (Bai *et al.*, 2011). Therefore, experimental soils were obtained from the top 0-20 cm of the sample field after DI and evaporation. Soil pH was measured with a pH meter (soil/deionized water ratio: 1:5), and soil EC was tested using a DDS-11A electrical conductivity meter (soil/deionized water ratio: 1:5). SAR, which is an important indicator in characterizing soil salinization, is defined as the ratio of the concentration of Na^+ to the square root of the concentration of Ca^{2+} and Mg^{2+} in the solution (Sposito & Mattigod, 1977). The contents of Na^+, Ca^{2+} and Mg^{2+} were measured by an atomic absorption spectrophotometer (Beijing TAS99F). Soil available N, P and K were extracted according to Bao (2008): N using the alkaline hydrolysis diffusion method, P using sodium bicarbonate method, and K using the ammonium acetate extraction method. Soil OM was measured by the potassium dichromate heating method.

The analysis of variance (ANOVA) was used to explore soil improvement differences by different soil amendments using SPSS 19.0 software with a significance level of $p<0.05$. The fitting procedures were carried out using Microsoft Office Excel 2007 and Grapher 8.0 software (http://www.goldensoftware.com).

Results

In this study, the effects of soil improvement were reflected in two aspects including improvement to soil properties and enhancement of soil nutrients. Improvement to soil properties was analyzed in terms of soil EC, pH and SAR values, which are key factors for plants survival. Soil nutrients comprised soil available N, P, K and OM, which are essential for plant growth.

Soil property improvement after DI

Table 5 shows that the soil EC decreased distinctively after DI under either the FW or BW treatment compared with the original soils (EC=8.02 dS/m). Under the FW treatment, the soil EC values of 16 treatments declined by 6.8-7.6 dS/m with an average decline of 91.7%; treatment T6 resulted in the lowest soil EC value (0.38 dS/m). Under the BW treatment, the soil EC values decreased by 6.2-7.3 dS/m with an average decline of 85.5%; treatment T5 resulted in the lowest soil EC value (0.76 dS/m). Both FW and BW reduced soil pH (Table 5). Under the FW treatment, compared with the original soils (pH=8.69), the soil pH values of 16 treatments were reduced by 0.23-0.89, with an average decrease of 6.1%. Under the BW treatment, the soil pH values declined by 0.44-1.02 with an average decrease of 8.0%.

The soil SAR value was highest in the CK among all treatments under either water source after DI (Table 5). Soil SAR decreased distinctively under either the FW or BW treatment compared with the original soils (SAR=40.6 $(mmol/L)^{0.5}$). Under the FW treatment, the soil SAR values of 16 treatments decreased by 32.7-37.6 $(mmol/L)^{0.5}$ on average, with an average decline of 89.4%. Treatment T12 produced the lowest soil SAR value (1.9 $(mmol/L)^{0.5}$). For the BW treatment, the soil SAR values decreased by 29.1-34.8 $(mmol/L)^{0.5}$ with an average decline of 77.9%. Treatment T3 resulted in the lowest soil SAR value (5.8 $(mmol/L)^{0.5}$).

Table 5. Effects of combination of different water sources (FW, BW) and soil amendments on soil chemical properties after drip irrigation ($p<0.05$).

Treatments	FW			BW		
	EC (dS/m)	pH	SAR (mmol/L)$^{0.5}$	EC (dS/m)	pH	SAR (mmol/L)$^{0.5}$
CK	0.53±0.03ef	8.56±0.06a	8.1±0.8a	0.76±0.13d	8.68±0.08a	12.9±1.1a
T1	0.48±0.04ab	8.46±0.12ab	7.9±0.6a	1.13±0.04c	8.10±0.14cd	9.6±1.0b
T2	0.66±0.03cd	8.29±0.07bc	6.1±0.4b	0.87±0.06d	8.18±0.04bc	9.7±0.6b
T3	0.87±0.06bc	8.07±0.03cd	3.2±0.1c	1.06±0.09cd	7.91±0.07cd	5.8±0.4d
T4	0.66±0.02cd	8.11±0.15cd	3.3±0.4c	0.98±0.07d	7.96±0.15bcd	9.0±0.7bc
T5	0.67±0.03cd	8.03±0.05cd	4.9±0.5bc	0.76±0.15d	8.25±0.09b	10.2±1.2b
T6	0.38±0.04f	8.27±0.14bc	5.1±0.4bc	0.88±0.02d	8.24±0.05b	10.0±1.3b
T7	0.50±0.02ef	8.27±0.06bc	5.1±0.3bc	1.08±0.08cd	8.00±0.08cd	9.8±0.8b
T8	0.60±0.06de	8.17±0.08bc	3.9±0.3c	1.66±0.09ab	7.67±0.13d	7.3±0.6cd
T9	0.47±0.08ef	8.23±0.09bc	5.1±0.4bc	1.06±0.13cd	8.02±0.09cd	10.7±0.9b
T10	0.86±0.15bc	8.08±0.07cd	3.5±0.4c	1.08±0.06cd	8.13±0.06cd	11.5±1.3ab
T11	0.41±0.06f	8.27±0.11bc	3.7±0.3c	1.23±0.03bc	7.93±0.07cd	8.8±0.6bc
T12	1.20±0.07a	7.80±0.1d	1.9±0.2d	1.84±0.04a	7.69±0.11d	6.2±0.5d
T13	0.55±0.09ef	8.19±0.09bc	4.4±0.3c	1.11±0.14c	8.11±0.05cd	10.8±1.4ab
T14	0.73±0.13cd	8.10±0.15cd	4.2±0.2c	1.11±0.08c	8.02±0.13cd	8.4±0.7c
T15	0.50±0.05ef	8.30±0.08bc	3.7±0.3c	1.25±0.02bc	7.96±0.07cd	8.1±0.6c
T16	1.09±0.1ab	7.99±0.07cd	2.9±0.4cd	1.51±0.03ab	7.80±0.6d	7.2±0.6cd

EC: soil electrical conductivity. SAR: sodium adsorption ratio.

Soil properties improvement after evaporation

After DI under the FW and BW treatments, soil columns were laid outdoors under a shelter for one month. Then, the soil EC, pH and SAR values were measured through sampling topsoils (0-20 cm).

Soil salinization occurred under both the FW and BW treatments (Table 6), compared with the soil columns before evaporation (Table 5). Under the FW treatment, the soil EC values decreased by 6.2-7.2 dS/m, with an average decline of 84.8%, in contrast to the original soils. However, the soil EC values of the 16 treatments increased by 97.3% on average; only CK exhibited no change compared with those before evaporation. The best treatment was CK. Under the BW treatment, soil EC values decreased by 4.1-7.2 dS/m with an average decline of 81.2% compared with the original soils. However, soil EC values of the 16 treatments increased by 27.8% on average compared with those before evaporation, and the best treatment was T5.

In terms of soil pH, the changes showed a different trend between the FW and BW treatments after evaporation (Table 6). Under the FW treatment, the soil pH values decreased by 0.20-0.75 (5.7% on average) in contrast to the original soils. Moreover, the soil pH values were increased by an average of 0.40% in comparison with those before evaporation (Table 5). The best treatment was T12. For the BW treatment, the soil pH values were decreased by 0.36-1.12 with an average of 9.8%, in contrast to the original soils. It should be noted that the soil pH values of the 16 treatments were decreased by 1.1% on average compared with those before evaporation (Table 5). The optimum treatment was T16.

Table 6 suggests that the soil SAR value of CK was the highest among all 16 treatments under either water source after evaporation, which is similar to those results after DI. For the FW treatment, the soil SAR values were decreased by 31.1-37.8 (mmol/L)$^{0.5}$ (86.3% on average) in contrast to the original soils. Compared with those before evaporation (Table 5), the soil SAR values of all the treatments were increased by 3.1% on average, except T2. For the BW treatment, the soil SAR values were decreased by 29.0-34.4 (mmol/L)$^{0.5}$ (78.8% on average) in contrast to the original soils, and decreased by 0.9% on average compared with those before evaporation.

Soil nutrients after evaporation

The experimental data showed that the accumulation of soil nutrients, including soil available N, P, K and soil OM, was significantly enhanced ($p<0.05$).

Fig. 3a indicates that under the FW treatment, the soil available N in the topsoils of the 16 treatments increased to 48.7-106.4 mg/kg compared with the

Table 6. Effects of combination of different water sources (FW, BW) and soil amendments on soil chemical indexes after one-month evaporation (p<0.05).

Treatment	FW			BW		
	EC (dS/m)	pH	SAR (mmol/L)$^{0.5}$	EC (dS/m)	pH	SAR (mmol/L)$^{0.5}$
CK	0.50±0.02d	8.27±0.05ab	11.3±1.1a	2.14±0.13bc	8.34±0.08a	17.2±1.2a
T1	1.08±0.14cd	8.49±0.12a	8.7±0.9b	1.02±0.04de	8.33±0.12a	8.7±0.5c
T2	0.92±0.03cd	8.40±0.07a	4.5±0.3cd	1.00±0.06de	8.12±0.04ab	8.3±0.7c
T3	0.92±0.07d	8.30±0.13ab	4.7±0.5cd	1.62±0.14cd	7.68±0.07b	6.1±0.4d
T4	1.56±0.04bc	8.15±0.05ab	5.4±0.4c	1.40±0.07cd	7.70±0.13b	6.4±0.5d
T5	0.83±0.05d	8.28±0.05ab	5.8±0.4c	0.80±0.05e	8.17±0.09ab	8.5±0.7c
T6	0.80±0.09d	8.32±0.12ab	5.2±0.4c	0.94±0.02de	8.00±0.05ab	7.3±0.6c
T7	1.18±0.11cd	8.23±0.06ab	5.8±0.5c	1.01±0.08de	7.92±0.08ab	8.0±0.5c
T8	1.42±0.05bc	8.16±0.08ab	5.2±0.3c	1.78±0.09cd	7.75±0.12b	8.5±0.6c
T9	1.19±0.08cd	8.19±0.09ab	7.7±0.6bc	1.19±0.03de	8.11±0.11ab	10.4±1.0bc
T10	1.12±0.15cd	8.18±0.07ab	4.5±0.3cd	1.08±0.06de	7.91±0.06ab	8.9±0.6b
T11	1.15±0.06cd	8.12±0.15ab	3.8±0.3d	1.84±0.03cd	7.88±0.07ab	10.1±1.2b
T12	1.84±0.03a	7.94±0.12b	2.7±0.3d	1.52±0.04cd	7.79±0.13ab	7.1±0.5d
T13	0.97±0.02cd	8.21±0.09ab	6.3±0.5c	1.69±0.12cd	7.90±0.05ab	11.5±1.1b
T14	1.38±0.07bc	8.08±0.12ab	9.5±0.7ab	1.17±0.08de	7.99±0.14ab	8.8±0.6c
T15	1.52±0.13bc	8.11±0.08ab	5.6±0.9c	2.14±0.02bc	7.74±0.07b	8.9±1.3c
T16	1.63±0.02ab	7.98±0.07b	3.4±0.8d	3.91±0.03a	7.57±0.16b	9.9±1.1c

FW and BW represent fresh water and brackish water, respectively; EC and SAR represent electrical conductivity and sodium adsorption ratio, respectively.

original soils (36.7 mg/kg), the soil available N of the 16 treatments increased by 32.6-190.0% while that of CK decreased by 8.2%, and T10 attained the highest soil available N content of 106.4 mg/kg. For the BW treatment, the content of soil available N ranged from 47.6 to 141.6 mg/kg, increasing by 29.6-285.7% compared with the original soils, and T13 achieved the highest soil available N content (141.6 mg/kg). Comparing the soil available nitrogen between FW and BW treatments (Fig. 3a), 12 of the 16 treatments exhibited a significant difference, which indicated that different water sources greatly affected soil available N content.

Under the FW treatment in Fig. 3b, the soil available P of the 16 treatments greatly increased to 235.6-692.0 mg/kg compared with the original soils (18.7 mg/kg). T10 reached the highest soil available P of 710.7 mg/kg. In the BW treatment, the content of soil available P ranged from 111.4 to 341.7 mg/kg, which is 5.0-17.3 times higher than that in the original soils, and T10 enabled the highest soil available P (341.7 mg/kg). There was significant difference between all the columns between FW and BW treatments except CK and T6.

Under the FW treatment in Fig. 3c, soil available K ranged from 512.0 to 785.0 mg/kg. Compared with original soils (691 mg/kg), the contents of soil available K of some treatments increased while others decreased. T13 resulted in the highest soil available K of 785.0 mg/kg. Under the BW treatment, the content of soil available K ranged from 404.9 to 832.2 mg/kg. Similar to the FW treatment, T13 also reached the highest content of soil available K (832.2 mg/kg). Most of the soil columns showed a significant difference between the FW and BW treatments (Fig. 3c).

The accumulation of soil OM is shown in Fig 3d, ranging from 13.4 to 27.1 g/kg under the FW treatment. In contrast to the original soils (25.3 g/kg), the soil OM of some treatments increased while others decreased; however, the soil OM of the 16 treatments were higher than that in CK (7.3 g/kg). T10 reached the highest soil OM of 27.1 g/kg. For the BW treatment, the content of soil OM reached 17.1-39.7 g/kg, corresponding to 0.8-3.3 times higher compared with that in CK (9.4 g/kg), and T13 reached the highest content of soil OM (39.7 g/kg). Fig. 3d shows that most of the columns had a significant difference in soil OM between the FW and BW treatments, and that the soil OM contents of all soil columns under the BW treatment were higher than those under the FW treatment.

Determination of superior water source

The above analyses showed that the FW treatment performed better than the BW treatment

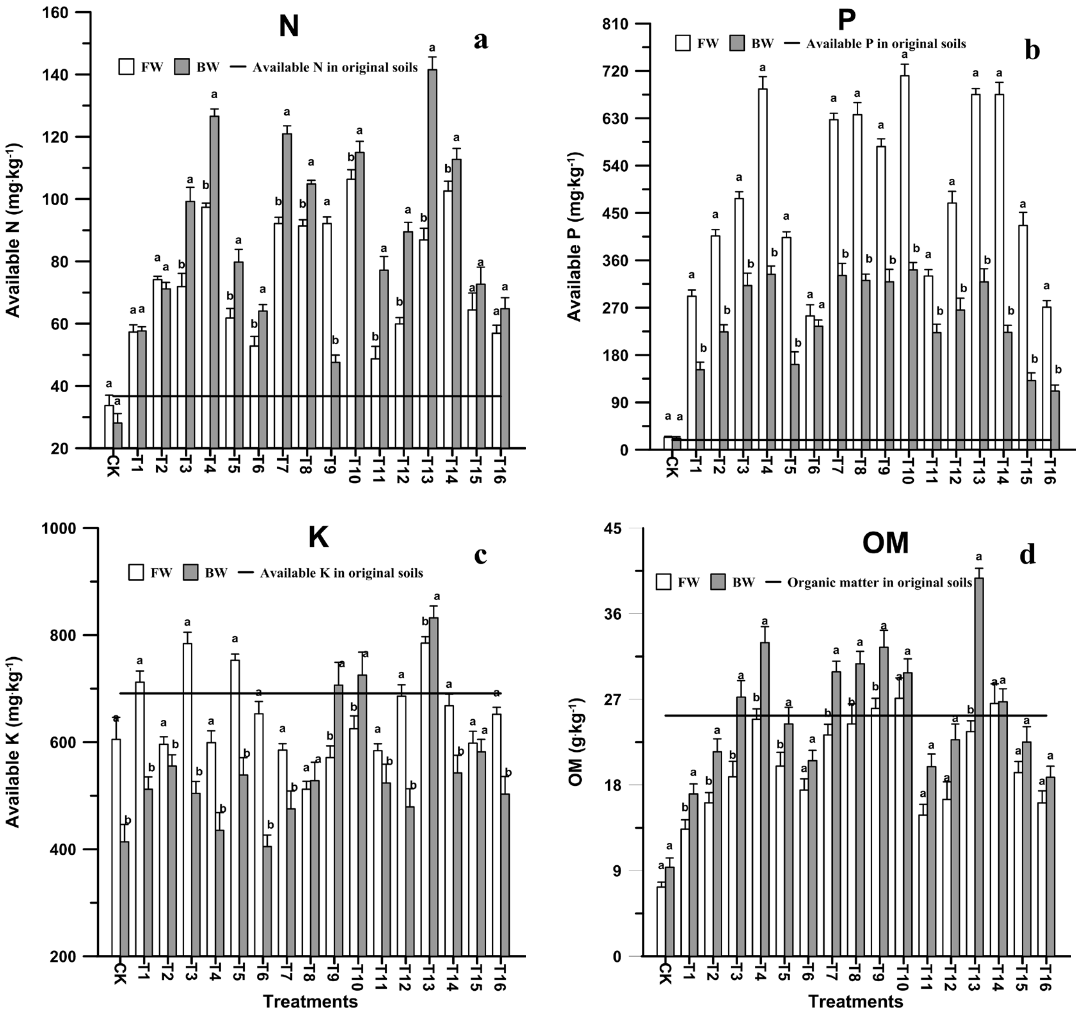

Figure 3. Effect of different treatments on soil nutrients including soil available N (nitrogen), P (phosphorus), K (potassium) and soil OM (organic matter) under FW (fresh water) and BW (brackish water) treatments after one-month evaporation. The black horizonal lines indicate the soil nutrient levels of original soils.

in decreasing the soil EC, while the latter performed better than the former in decreasing the soil pH after DI (Table 5). After evaporation, however, soil salt and alkalinity under the FW treatment increased in most of the treatments (Table 6), *i.e.*, soil EC, pH and SAR values under the FW treatment showed greater increases than those under the BW treatment. Soil pH and SAR under the BW treatment even decreased after evaporation (Table 6). In terms of soil nutrients, soil available N and P were enhanced while soil available K either decreased or increased under both water treatments. However, the studied saline-alkali soils were rich in soil available K (Zhang *et al.*, 2012). In addition, the soil OM of the BW treatment was higher than that of the FW treatment (Fig. 3d): the additional fact that brackish water was easily acquired and thus would decrease soil reclamation costs in coastal areas proved the great potential of BW in improving saline-alkali soils (Yao *et al.*, 2014).

Determination of optimum combination of amendments under BW treatment

According to the above results, orthogonal analysis was performed on all the indices after evaporation in order to obtain the best combination of the amendments under the BW treatment.

Effect of different amendments on soil chemical properties

The ANOVA analysis showed that only phosphogypsum had a significant effect on soil EC among the different amendments and that soil EC was influenced in the order of B>A>E>D>C, which showed that phosphogypsum was the most important factor affecting

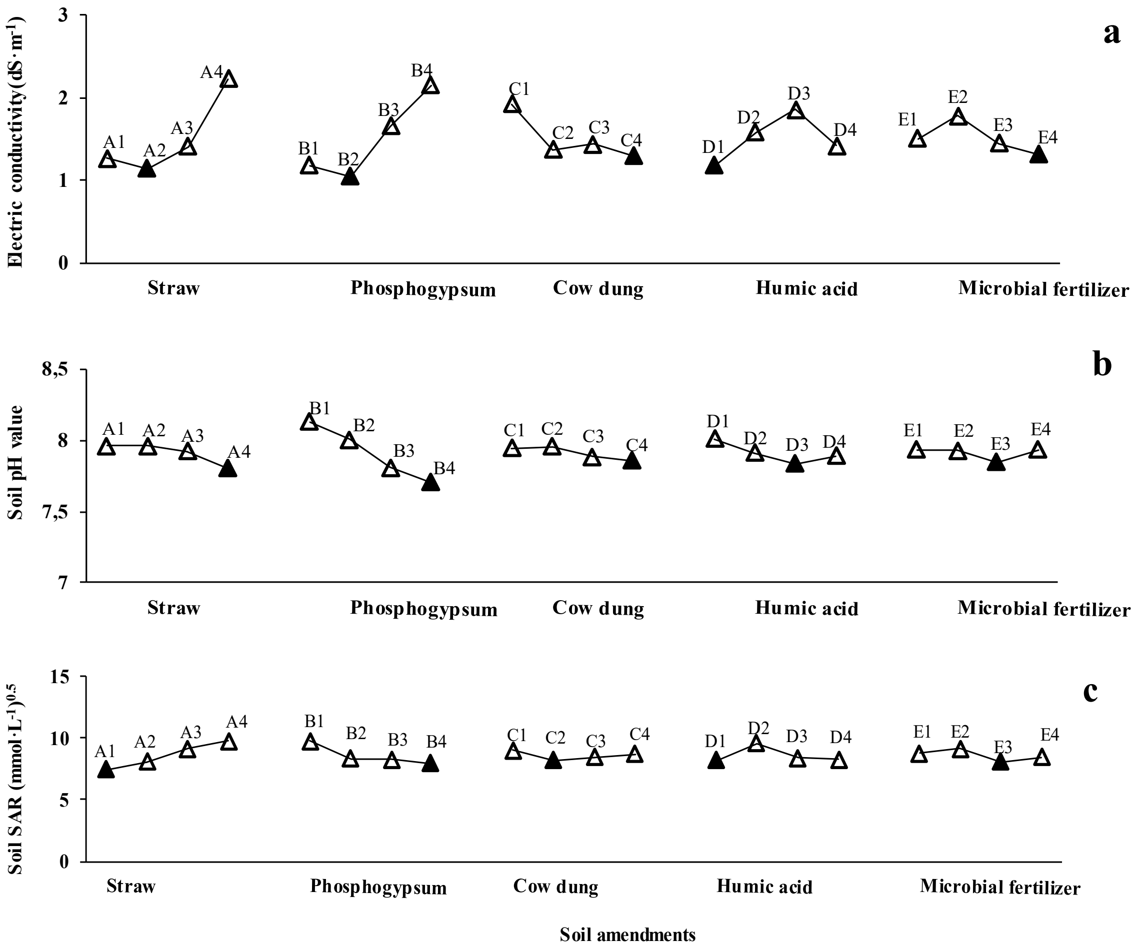

Figure 4. Effect of different amendments on soil chemical properties (soil electrical conductivity (EC), pH and sodium adsorption ratio (SAR) under BW treatment after one-month evaporation. The black solid triangles represent the optimal levels of each soil amendment for soil chemical properties.

soil EC (straw was the second). Fig. 4a indicates that the soil EC decreased first and then increased linearly with the increase in phosphogypsum and straw application and that the optimal levels were B2 and A2. Other indices changed slightly, which indicated that they had little effect on soil EC. Therefore, A2B2C4D1E4 was the optimal combination for soil EC.

According to the variance analyses (p<0.05), phosphogypsum had a significant effect on soil pH, which was influenced in the order of B>C>A>D>E. It can be seen that phosphogypsum was still the most important factor affecting soil pH. The result showed that phosphogypsum played an important role in regulating soil pH value. Based on comprehensive consideration (Fig. 4b), A4B4C4D3E3 was the best combination for decreasing soil pH.

The ANOVA analysis indicated that all amendments had no significant effect on soil SAR, which was influenced in the order of A>B>D>E>C. Fig. 4c indicates that straw was the major factor for soil SAR, and phosphogypsum was the second. With the increase in straw application, soil SAR value increased possibly because the straw could absorb brackish water. With the increase in phosphogypsum application, SAR decreased gradually due to the increase in Ca^{2+} concentration. Finally, A1B4C2D1E3 was chosen as the optimal combination for reducing soil SAR.

Effect of different amendments on soil nutrients

Cow dung had a significant effect on soil available N (p<0.05), which was influenced in the order of C>E>D>A>B. Fig. 5a shows that cow dung is the greatest influencing factor on increasing soil available N, *i.e.*, the more cow dung applied, the higher soil available N content. Hence, C4 was chosen as the optimal level, and A4B4C4D2E4 was the best treatment for soil available N.

The results of the ANOVA analysis indicated that straw and cow dung were significant for soil available P, which was influenced in the order of C>A>E>D>B. Fig. 5b suggests that soil available P gradually increased as cow dung application increased; the value increased first and decreased afterwards with application of straw. Therefore, A3B4C4D2E3 was the best treatment for soil available P.

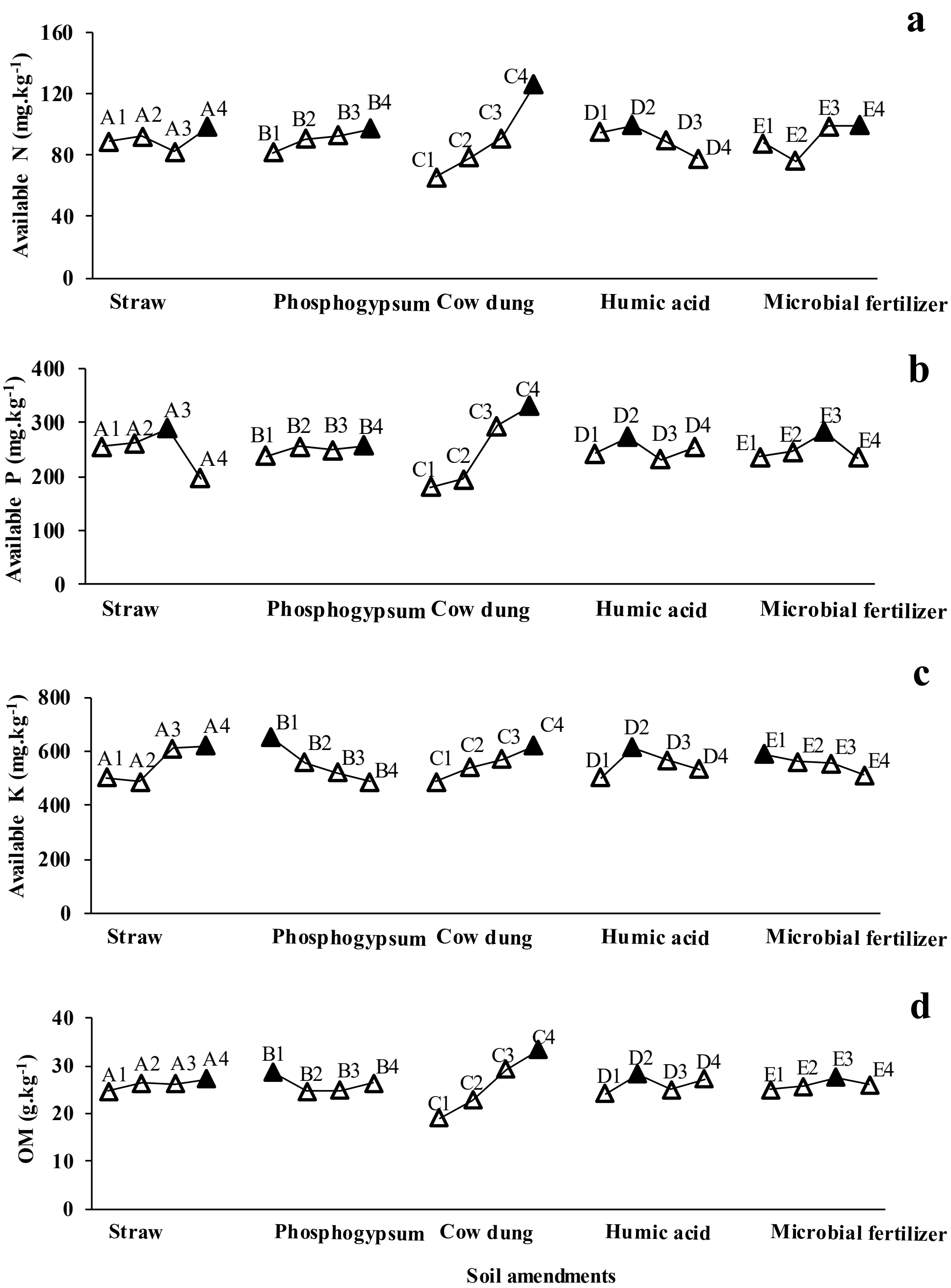

Figure 5. Effect of different amendments on soil nutrients (soil available N (nitrogen), P (phosphorus), K (potassium) and soil organic matter (OM)) under BW (brackish water) treatment after one-month evaporation. The black solid triangles represent the optimal levels of each soil amendment for soil nutrients.

All amendments had no significant effect on soil available K, which was influenced in the order of B>A>C>D>E, indicating that phosphogypsum exerted the greatest effect on soil available K: with the increase in phosphogypsum application, the content of soil available K decreased (Fig. 5c). A4B1C4D2E1 was then the best treatment for soil available K.

Variance analysis suggested that cow dung had a significant effect on soil OM, which was influenced in the order of C>D>B>E>A. Similar to soil available N (Fig. 5a), Fig. 5d shows that cow dung was also the greatest influence factor on increasing soil OM. The best combination was A4B1C4D2E3 for soil OM.

Determination of optimal combination

It is necessary to take into account all the indicators in order to achieve the purpose of improving saline-alkali land. Therefore, the optimum combinations were also determined on the basis of the degree sequence and a comprehensive consideration including cost and practicality.

Straw (A) significantly affected only soil available P ($p<0.05$), and A3 was the best level because it had no significant influence on other soil indicators. Therefore, the A3 level was chosen. Phosphogypsum (B) had a significant effect on soil EC and pH ($p<0.05$), and it was the first influencing factor for soil EC and pH, B2 was the best level for soil EC, while B4 was best for soil pH value. As B2 increased soil pH value by 3.9% more than B4, while the latter increased soil EC by 105.9% more than the former, B2 was chosen. Cow dung (C) had significant influence on soil available N, P and OM ($p<0.05$). It was the first influencing factor for those three indicators, and C4 performed at the best level. Therefore, the C4 level was chosen. Humic acid (D) had no significant influence on any indicators ($p<0.05$), but it was the second effective factor on soil pH value and soil OM: D2 was the best level for soil nutrients with D3 for soil pH value. Since D2 increased soil pH value by 1.0% more than D3, while the latter decreased soil OM by 10.4%, the D2 level was chosen. Microbial fertilizer (E), similar to humic acid, had no significant effect on any indice ($p<0.05$). As microbial fertilizer was the second effect factor on soil available N, and E4 was the best level, the E4 level was chosen by comprehensive consideration. Therefore the optimum formula was A3B2C4D2E4 under BW treatment.

Discussion

As they are vital agricultural land reserves, the studies of highly saline-alkali soils have received much attention in the world (Agassi *et al.*, 1986; Qadir *et al.*, 1996; Gupta *et al.*, 2016; Rameshwaran *et al.*, 2016). Applying soil amendments as a common method with low cost and potentially significant effectiveness could solve the problems of soil salinity. Due to the scarcity of fresh water in coastal areas, low quality water (such as saline groundwater) has been widely utilized (Beltrán, 1999; Verma *et al.*, 2012; Wang *et al.*, 2016). The results of this experiment showed that DI with both FW and BW could improve soil salinity and alkalinity and enhance soil nutrient contents through a proven combination of soil amendments. Furthermore, the results showed that compared with the FW treatment, soil SAR and pH values were further decreased while soil OM content was enhanced after evaporation under the BW treatment, which was beneficial to the improvement of saline alkali soils.

Effects of soil amendments

Straw and cow dung can be decomposed to improve soil fertility by increasing soil nutrient content (Rao & Pathak, 1996). Specifically, in this work, straw had a significant effect on the improvement of soil available P (for 1-3 levels), while cow dung had a significant effect on soil available N, P and soil OM ($p<0.05$).

As a byproduct of the ammonium phosphate industry, phosphogypsum has been widely used due to its low cost and potential to improve soil salinity (Al-Karaki & Al-Omoush, 2002). Agassi *et al.* (1986) found that application of phosphogypsum can prevent soil hardening and reduce sodium ion concentration in the soil. The study of Wu *et al.* (2012) indicated that phosphogypsum could increase soil nutrients and improve soil salinity conditions, *i.e.*, Ca^{2+}, suitable for crops, replaced the unsuitable Na^+, and Na^+ was eventually washed away by water. Moreover, CO_3^{2-} and HCO_3^- decreased gradually while SO_4^{2-} (harmless to crops) increased, and soil pH was effectively improved. Similar results appeared in our experiments (see Table 1), in which phosphogypsum demonstrated a significant influence on soil EC and pH ($p<0.05$).

In terms of humic acid, Sun *et al.* (2013) reported that humic acid could decrease soil pH by releasing H^+ and OH^- ions to generate H_2O as well as improve soil structure and heighten soil permeability, which promoted the dissolution of Na^+, and therefore reduced soil EC value. However, in the present work, the effect of humic acid was not significant for soil EC, pH and SAR under BW treatment. This may be related to the different water sources and antagonistic effects of different soil amendments.

Microbial fertilizer increases soil OM and organic acid via decomposition, which could provide nutrition for microorganism and improve physical and chemical properties of saline-alkali soils (Sun, 2010; Wu *et al.*, 2011). Our experimental results showed that microbial fertilizer had no significant effect on either soil properties (pH, EC and SAR) or soil nutrients (soil available N, P, K and soil OM) under the BW treatment ($p<0.05$). Possible reasons for this result were that the effect of microbial fertilizer largely depends on the living environment of the microorganism, *e.g.*, soil temperature, soil water content, soil salinity and OM, soil pH and illumination (Liu, 2008). In fact, microbial fertilizer is not actual fertilizer; it provides nutrients indirectly through the living activities of microorganism, which enhance soil nutrient level. Considering that five soil amendments were mixed together to improve experimental soils, the effectiveness of microbial fertilizer could be discounted.

Limitations and prospects

In our study, a combination of five soil amendments with fresh and brackish water under DI treatment was applied for saline-alkali soil improvement. Considering the cost and convenience of soil reclamation materials, the optimal soil amendment combination under brackish water was determined by orthogonal analysis in terms of soil EC, pH, SAR and soil nutrients. Those indicators are considered the most important factors affecting plant survival and growth. Therefore, soil physical properties such as soil bulk density have not been discussed in this study, which might have some effects on the study conclusion. For saline water irrigation, it was reported in previous studies that irrigating with saline water presents risks such as salinity hazards or salt toxicity for plants (Sairam & Tyagi, 2004) while other scientists reached the opposite conclusion (Li C. *et al.*, 2015).

Since the topsoil (0-20 cm) is the soil region for plants, this study focused on the improvement of topsoil: the salt permeated downwards, moving to the deeper soil layer and causing salt accumulation. To solve this problem in the field, underground pipes are usually laid to drain away the applied salty water, which finally flowes into small wells, which is excavated as a component of a subsurface drainage system.

In conclusion, brackish water, with a lower cost, showed great potential to improve saline-alkali soils, especially regarding decreases in soil alkalinity and SAR, compared with fresh water. The optimum combination of soil amendments was A3B2C4D2E4 (0.03 m^3/m^2 of straw, 3 kg/m^2 of phosphogypsum, 0.04 m^3/m^2 of cow dung, 0.6 kg/m^2 of humic acid and 0.18 kg/m^2 of microbial fertilizer) under the brackish water treatment. As soil quality improvement is complicated and time-varying process, further work should be conducted to examine soil quality alteration in the longer period, in terms of soil property improvement, soil nutrient enhancement, and conditions in the field. The conclusions could provide references for improving saline-alkali soils especially for brackish water use, and promote the sustainable development of ecology, agriculture and economy in the coastal saline areas of East China.

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References

Agassi M, Shainberg I, Morin J, 1986. Effect of powdered phosphogypsum on the infiltration rate of sodic soils. Irrig Sci 7 (1): 53-61. https://doi.org/10.1007/BF00255694

Al-Karaki GN, Al-Omoush M, 2002. Wheat response to phosphogypsum and mycorrhizal fungi in alkaline soil. J Plant Nutr 25 (4): 873-883. https://doi.org/10.1081/PLN-120002966

Bai W, Sun ZX, Zheng JM, Liu Y, Hou ZY, Feng LS, Yang N, 2011. Soil plough layers and soil nutrients in Western Liaoning. Soils 43 (5): 714-719.

Bao SD, 2008. Soil agriculturalization analysis. China Agriculture Press, Beijing. 176 pp.

Beltrán JM, 1999. Irrigation with saline water: benefits and environmental impact. Agr Water Manage 40: 183-194. https://doi.org/10.1016/S0378-3774(98)00120-6

Chaganti VN, Crohn DM, Šimůnek J, 2015. Leaching and reclamation of a biochar and compost amended saline–sodic soil with moderate SAR reclaimed water. Agr Water Manage 158: 255-265. https://doi.org/10.1016/j.agwat.2015.05.016

Clark RB, Baligar VC, 2003. Growth of forage legumes and grasses in acidic soil amended with flue gas desulfurization products. Commun Soil Sci Plant 34 (1-2): 157-180. https://doi.org/10.1081/CSS-120017423

Gu JF, 2013. Effect of microbiological fertilizer on salinized soil: Yangzhou University.

Gupta M, Srivastava PK, Shikha, Niranjan A, Tewari, SK, 2016. Use of a bioaugmented organic soil amendment in combination with gypsum for withania somnifera growth on sodic soil. Pedosphere 26 (3): 299-309. https://doi.org/10.1016/S1002-0160(15)60044-3

Kelly WP, Brown SM, 1934. Principles governing the reclamation of alkali soils. Hilgardia (5): 149-177. https://doi.org/10.3733/hilg.v08n05p149

Li CJ, Lei JQ, Zhao Y, Xu XW, Li SY, 2015. Effect of saline water irrigation on soil development and plant growth in the Taklimakan Desert Highway shelterbelt. Soil Till Res 146, Part A: 99-107.

Li XB, Kang YH, Wan SQ, Chen XL, Xu JC, 2015. Effect of drip-irrigation with saline water on Chinese rose (Rosa chinensis) during reclamation of very heavy coastal saline soil in a field trial. Sci. Hortic-Amsterdam. 186: 163-171. https://doi.org/10.1016/j.scienta.2015.02.024

Liu LL, 2008. Production technology and biology of microbial fertilizer. Science Press, Beijing.

Liu LP, Long XH, Shao HB, Liu ZP, Tao Y, Zhou QS, Zong JQ, 2015. Ameliorants improve saline–alkaline soils on a large scale in northern Jiangsu Province, China. Ecol Eng 81: 328-334. https://doi.org/10.1016/j.ecoleng.2015.04.032

Liu YH, Wang XP, Li Q, Zhang GX, Lu XL,2015. Study on rapid desalting of muddy coastal heavy solonchack with low cost. Res Soil Water Conserv 22 (1): 168-171.

Lu SY, Chen FX, Ngo, HH, Guo WS, Feng CP, Wu JN, Zheng BH, 2016. Effect of straw and polyacrylamide on the stability of land/water ecotone soil and the field implementation. Ecol Eng 94: 12-21. https://doi.org/10.1016/j.ecoleng.2016.05.076

Luo JQ, Wang LL, Li QS, Zhang QK, He BY, Wang Y, Qin LP, Li SS, 2015. Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil Till Res 149: 12-20. https://doi.org/10.1016/j.still.2014.12.014

Mao YM, Li XP, Dick WA, Chen LM, 2016. Remediation of saline–sodic soil with flue gas desulfurization gypsum in a reclaimed tidal flat of southeast China. J Environ Sci-China 45: 224-232. https://doi.org/10.1016/j.jes.2016.01.006

Qadir M, Qureshi RH, Ahmad N,1996. Reclamation of a saline-sodic soil by gypsum and Leptochloa fusca. Geoderma 74 (3-4): 207-217. https://doi.org/10.1016/S0016-7061(96)00061-4

Rameshwaran P, Tepe A, Yazar A, Ragab R, 2016. Effects of drip-irrigation regimes with saline water on pepper productivity and soil salinity under greenhouse conditions. Sci Hortic-Amsterdam 199: 114-123. https://doi.org/10.1016/j.scienta.2015.12.007

Rao DLN, Pathak H, 1996. Ameliorative influence of organic matter on biological activity of salt-affected soils. Arid Soil Res Rehab 10 (4): 311-319. https://doi.org/10.1080/15324989609381446

Rengasamy P, 2006. World salinization with emphasis on Australia. J Exp Bot 57 (5): 1017-1023. https://doi.org/10.1093/jxb/erj108

Sairam RK, Tyagi A, 2004. Physiology and molecular biology of salinity stress tolerance in plants. Curr Sci India (86): 407-442.

Shainberg I, Gal M, Ferreira AG, Goldstein D,1991. Effect of water quality and amendments on the hydraulic properties and erosion from several mediterranean soils. Soil Tech 4 (2): 135-146. https://doi.org/10.1016/0933-3630(91)90025-I

Sposito G, Mattigod SV, 1977. On the chemical foundation of the sodium adsorption ratio. Soil Sci Soc Am J 41 (2): 323-329. https://doi.org/10.2136/sssaj1977.03615995004100020030x

Sun JJ, 2010. Distribution of microorganism and modified effects of microfertilizer on saline soil in coastal area: Tianjin University of Technology, China.

Sun ZJ, Huang ZB, Lu ZH, 2013. Improvement effects of different environmental materials on coastal saline-alkali soil in the Yellow River Delta. J Soil Water Conserv 27 (4): 186-190.

Tong Y, Chen K, Yang RB, 2014. The application progress of humic acid in ecological environment. Humic Acid 1: 9-13.

Verma AK, Gupta SK, Isaac RK, 2012. Use of saline water for irrigation in monsoon climate and deep water table regions: Simulation modeling with SWAP. Agr Water Manage 115: 186-193. https://doi.org/10.1016/j.agwat.2012.09.005

Wang QM, Huo ZL, Zhang LD, Wang JH, Zhao Y, 2016. Impact of saline water irrigation on water use efficiency and soil salt accumulation for spring maize in arid regions of China. Agr Water Manage 163: 125-138. https://doi.org/10.1016/j.agwat.2015.09.012

Wang ZF, Wang H, 2012. Inflatable wing design parameter optimization using orthogonal testing and support vector machines. Chinese J Aeronaut 25 (6): 887-895. https://doi.org/10.1016/S1000-9361(11)60459-7

Weng YL, Gong P, Zhu ZL, 2010. A spectral index for estimating soil salinity in the Yellow River Delta Region of China using EO-1 hyperion data. Pedosphere 20 (3): 378-388. https://doi.org/10.1016/S1002-0160(10)60027-6

Wu HS, Chen XQ, Zhou XD, Yang XN, Shi YH, Man J, Wu HB, 2012. Effects of soil amendment Phosphogypsum on physical and chemical properties and wheat growth in coastal saline soil in Rudong, Jiangsu. Acta Pedologica Sinica 49 (6): 1262-1266.

Wu ZS, Zhao YF, Kaleem I, Li C, 2011. Preparation of calcium–alginate microcapsuled microbial fertilizer coating Klebsiella oxytoca Rs-5 and its performance under salinity stress. Eur J Soil Biol 47 (2): 152-159. https://doi.org/10.1016/j.ejsobi.2010.11.008

Xiong XR, Araya A, Zhang HJ, Araya K, Teramoto C, Ohmiya K, Liu F, Jia HB, Zhang CF, Zhu BG, Wang NN, Meng QY, Yang SC, 2012. Improvement of salt-affected soils by deep tillage: Part 2: large-scale field tests in a sodic soil (Solonetz) region. Eng Agr Environ Food 5 (1): 29-35.

Yao RJ, Yang JS, Zhang TJ, Hong LZ, Wang MW, Yu SP, Wang XP, 2014. Studies on soil water and salt balances and scenarios simulation using SaltMod in a coastal reclaimed farming area of eastern China. Agr Water Manage 131: 115-123. https://doi.org/10.1016/j.agwat.2013.09.014

Zhang GX, Wang XP, Liu YH, Wang GZ, 2012. Analysis and evaluation of soil nutrients in coastal areas of Hebei. Tianjin Agricultural Sciences 18 (3): 59-62.