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Closing Yield Gaps through Soil Improvement for Maize Production in Coastal Saline Soil

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Abstract: As efforts to close crop production yield gaps increase, the need has emerged to identify cost-effective strategies to reduce yield losses through soil improvement. Maize (*Zea mays* L.) production in coastal saline soil is limited by high salinity and high pH, and a limited number of soil amendment options are available. We performed a field experiment in 2015 and 2016 to evaluate the ability of combined flue gas desulfurization gypsum and furfural residue application (CA) to reduce the maize yield gap and improve soil properties. We carried out the same amendment treatments (CA and no amendment as a control) under moderate (electrical conductivity ($EC_{1:1}$) ≈ 4 dS m^{-1}) and high ($EC_{1:1} \approx 6$ dS m^{-1}) salinity levels. Averaged over all salinity levels and years, maize yields increased from 32.6% of yield potential in the control to 44.2% with the CA treatments. Post-harvest CA treatment increased the calcium (Ca^{2+}) and soil organic carbon (SOC) contents while decreasing the sodium (Na^+) content and pH in the upper soil layer. Corresponding nitrogen, phosphorus, potassium, calcium, and magnesium accumulations in maize were significantly increased, and Na accumulation was decreased in the CA group compared with the control. The economic return associated with CA treatment increased by 215 \$ ha^{-1} at the high salinity level compared with the control, but decreased at the moderate salinity level because of the minor increase in yield. The results of this study provide insight into the reduction of yield gaps by addressing soil constraints.

Keywords: soil salinity; amendments; crop growth and development; grain yield

1. Introduction

Significant gaps exist between potential yields and farmers' actual yields (i.e., yield gaps) [1,2]. Many studies have focused on the optimization of crop and fertilizer management to close yield gaps [1,3,4]. However, the effects of optimal management are limited by various environmental and soil constraints, and soil salinity is a major stressor adversely affecting plant growth and crop productivity. The Yellow River Delta (YRD) area has been affected by severe soil salinization issues, with high groundwater salinity (5–30 g L^{-1}), shallow groundwater levels (1–2 m below the soil surface), and low organic carbon content (averaged 6.09 g kg^{-1}) [5–8]. In this region, high soil pH and an excess of sodium (Na) ions result in poor soil structure and low water infiltration, inhibiting crop growth and nutrient absorption and, ultimately, reducing crop yields [9–13].

Soil salinity adversely affects crops through two processes: Osmotic stress and ionic toxicity [14]. Osmotic stress delays germination, reduces the seedling emergence rate, and inhibits early seedling growth [15,16]. High sodium levels in the rhizosphere result in ion toxicity and ionic imbalance in terms of uptake competition of Na with nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg), inhibiting leaf development and accelerating the senescence of transpiring leaves [17]. These processes affect photosynthesis and dry matter accumulation, reduce grain number and grain weight, and decrease grain yield in maize [18,19].

Salt leaching with flood irrigation from the Yellow River is a common practice used by local farmers to mitigate salt damage to maize and to close yield gaps [20]; the performance of this practice, however, is limited due to the adsorption of soil Na^+ into the clay, coupled with poor soil permeability [21]. The application of flue gas desulfurization gypsum (FGDG) can replace Na^+ with Ca^{2+} at the cation exchange site, thereby increasing the flocculation of clay particles near the soil surface [22,23]. However, the movement of ions through the soil is limited in areas with low soil organic carbon (SOC) content [24]. Furthermore, the application of large quantities of FGDG might result in weak aggregate stability [25,26], increase bulk density, and further limit salt leaching out of the root zone [27]. To address these technological limitations, furfural residue (FR), a byproduct of furfural production from corn cobs by acid catalysis at high temperatures, has been used. FR is rich in organic carbon and can increase the SOC content, reduce soil bulk density, and lower soil pH [24].

Here, we theorized that combined FGDG and FR application (CA treatment) would mitigate salt damage to maize, increasing early seedling growth and ear number, reducing ionic imbalance, and increasing late growth, grain number, and grain weight. Furthermore, we expected that CA treatment could improve soil properties by lowering Na^+ and pH levels and increasing Ca^{2+} and SOC contents. We also investigated whether these effects differed depending on the salinity level and crop season. The results are expected to provide insight into the effective reclamation of coastal saline soil for food production and soil sustainability.

2. Materials and Methods

2.1. Experimental Sites

The field experiment was conducted in 2015 and 2016 at the Kenli County Seed Multiplication Farm ($37^{\circ}24' - 38^{\circ}10'$ N, $118^{\circ}15' - 119^{\circ}19'$ E), situated in the YRD region, northeastern Shandong Province, China. This region has a warm temperate monsoon continental climate with low annual rainfall, concentrated in the summer. Figure 1 shows the precipitation, evaporation, and average daily temperature during the spring maize growing season. The precipitation levels during the growing seasons in 2015 and 2016 were 595 and 532 mm, respectively, and the evaporation levels in those years were 529 and 542 mm, respectively (data from the China Meteorological Data Network).

A basic soil analysis revealed differences in the salinity level and physicochemical properties. The electrical conductivity using 1:1 water extract ($\text{EC}_{1:1}$) was about 4 and 6 dS m^{-1} for two experimental sites. The soil texture was silt loam [28]. The bulk density was 1.47 and 1.55 g cm^{-3} for two experimental sites at the 0–20 cm soil layer, respectively. We calculated the electric conductivity of saturated soil extract (EC_e) of 13.4 and 22.8 dS m^{-1} in accordance with the dilution law [29]. According to the classification of the US Salinity Laboratory for soil salinity (the EC_e of moderate and high salinity was 8–16 and 16–32 dS m^{-1}) [30], the salinity levels of two experimental sites were moderate and high salinity. Table 1 presents the basic physicochemical properties in the upper 0–20 and 20–40 cm of the soil profiles at the two experimental sites.

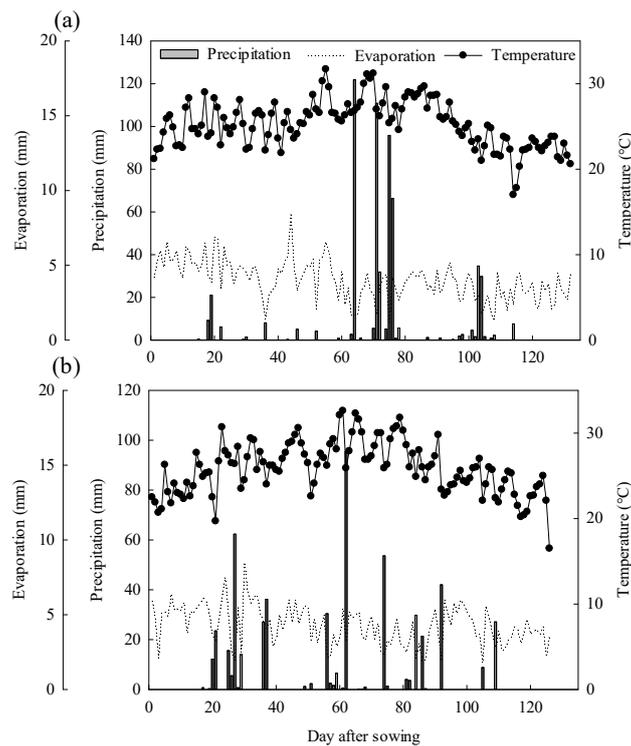


Figure 1. Precipitation, evaporation, and daily mean temperature during the spring maize growing seasons (May–October) in 2015 (a) and 2016 (b) in Kenli County.

Table 1. Basic physical and chemical properties in the top 0–20 cm and 20–40 cm soil profile before sowing in 2015 with moderate and high salinity levels.

Characteristics	Moderate Salinity Level		High Salinity Level	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Sand (%)	69.1	89.4	73.5	81.5
Silt (%)	28.0	9.21	24.0	16.8
Clay (%)	2.86	1.43	2.45	1.72
pH	8.19	8.33	8.10	8.35
EC (dS m ⁻¹)	3.91	4.05	6.30	6.25
Organic carbon (g kg ⁻¹)	4.33	0.62	2.99	0.75
Total N (g kg ⁻¹)	0.67	0.36	0.53	0.22
Olsen-P (mg kg ⁻¹)	4.98	1.95	6.72	1.85
Exchangeable K (mg kg ⁻¹)	77	25	110	50
Exchangeable Ca (mg kg ⁻¹)	3760	2701	3567	3409
Exchangeable Na (mg kg ⁻¹)	426	270	777	1094
Exchangeable Mg (mg kg ⁻¹)	467	211	527	515

2.2. FGDG and FR

FGDG is an industrial coal byproduct used to treat sulfur dioxide in flue gas in power generation (Thermal power plant in Dongying, China). It has the following chemical properties: pH, 8.00; EC_{1:1}, 17.3 dS m⁻¹; exchangeable Ca, 49.5 g kg⁻¹; exchangeable Na, 444 mg kg⁻¹; and exchangeable Mg, 572 mg kg⁻¹. As the waste residue discharged from furfural production, FR is extracted by a series of chemical reactions between crushed corncob and sulfuric acid (Shandong Green Ant Bio-organic Fertilizer Co., Ltd., Jinan, China). It has the following chemical properties: pH, 3.30; EC_{1:1}, 32.1 dS m⁻¹; exchangeable Ca, 177 mg kg⁻¹; exchangeable Na, 244 mg kg⁻¹; exchangeable Mg, 73.0 mg kg⁻¹; exchangeable K, 727 mg kg⁻¹; SOC, 325 g kg⁻¹; total N, 7.50 g kg⁻¹; and Olsen-P, 0.2 mg kg⁻¹. The

testing methods of FGDG and FR were consistent with that of soil. According to previous studies and calculation of the gypsum requirement, the dosages of FGDG and FR in this study were determined to be 15 and 7.5 Mg ha⁻¹, respectively [21,24].

2.3. Experimental Design and Field Management

The field experiment involved two treatments: Combined application of 15 Mg ha⁻¹ FGDG and 7.5 Mg ha⁻¹ FR (CA treatment) and no amendment as a control. Each treatment was carried out at different salinity levels (moderate and high). The area of each plot was 81 m² (9 m × 9 m), and the plot treatments were allocated using a randomized block design with three replicates. The spring maize (*Zea mays* L.) cultivar Zhengdan 958 was used in both cropping seasons, and the sowing dates were 20 May 2015, and 15 May 2016.

The planting density was about 7.5×10^4 plant ha⁻¹ (row spacing, 0.6 m; plant spacing, 0.22 m). During the entire spring maize growth period, the total amount of fertilizer applied was 200 kg N ha⁻¹: 135 kg P₂O₅ ha⁻¹ as urea (46% N) and mono-ammonium phosphate (10% N and 50% P₂O₅), and 150 kg K₂O ha⁻¹ as potassium sulfate. N was applied three times per growth season: 45 kg N ha⁻¹ before sowing, 90 kg N ha⁻¹ at the six-leaf (V6) stage, and 65 kg N ha⁻¹ at the tasseling (VT) stage. P and K were applied twice per growth season: 90 kg P₂O₅ ha⁻¹ and 90 kg K₂O ha⁻¹ before sowing, and 45 kg P₂O₅ ha⁻¹ and 60 kg K₂O ha⁻¹ at the V6 stage.

The plots were irrigated with 250 mm water from the Yellow River once at 20 days before sowing each year using the flood irrigation method. All fertilizers (45 kg N ha⁻¹, 90 kg P₂O₅ ha⁻¹, and 90 kg K₂O ha⁻¹) and amendment used before sowing were spread manually and evenly over the plots and mixed immediately into soil plowed (to 0.20 m depth) with a rotary cultivator. At the V6 and VT stages, all fertilizers were applied to the soil by ditching (to 0.1 m depth) between the corn rows with a furrowing machine. During the experiment, insects and weeds were controlled according to local agronomic practices. All maize residues excluding cob were crushed by a grinder and returned to the field, which was then plowed deeply (to 0.25 m) in 2014 and each year thereafter.

2.4. Sampling and Laboratory Procedures

Soil samples from the 0–20 and 20–40 cm soil layers were collected before sowing and at maturity. After air drying, the soil samples were crushed and passed through a 20-mesh sieve. These samples were used to test the soil particle size distribution, pH, EC_{1:1}, and exchangeable cations (K, Ca, Na, and Mg). Then, the soil samples were ground and passed through a 100-mesh sieve to measure total N and organic carbon. The particle size distribution of soil samples was determined using a laser particle size analyzer (Winner 2006A, China) [31]. Soil pH was measured using a pH meter (SevenExcellence, Mettler-Toledo, China) by extraction (1:2.5 ratio of soil to 0.01 mol L⁻¹ CaCl₂), and EC_{1:1} was measured using an EC meter (Mettler-Toledo, China) by extraction (1:1 ratio of soil to water). Available P was measured according to Olsen et al. [32] using the ammonium molybdate–ascorbic acid method [33]. Exchangeable cations (K, Ca, Na, and Mg) were measured after extraction in 1 mol L⁻¹ ammonium acetate (pH = 7.0) and analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES; OPTIMA 3300 DV; Perkin-Elmer, USA) [34]. Soil total N and SOC were determined using a vario MACRO elemental analyzer (Elementar, Langenselbold, Germany).

At each of the V6, VT, and mature (R6) stages, six plants near the middle of each plot were clipped for the determination of aboveground biomass; the samples were dried at 60–65 °C until they had reached a constant weight. At the R6 stage, an area of 12 m² (5 m × 2.4 m) in the middle of each plot was harvested manually to determine the grain yield (15.5% water content) and yield components, by counting of the harvested ears. Straw and grain samples collected at the R6 stage were ground with a grinder for nutritional analysis. The N content was determined by the Kjeldahl method [35]. The P, K, Ca, Mg, and Na contents were determined by ICP-OES though digesting with HNO₃-H₂O₂ in a microwave-accelerated reaction system (CEM Corporation, Matthews, NC, USA) [36].

2.5. Model Development and Preliminary Validation

The hybrid maize model was used to simulate maize development and growth using a daily time step and to estimate yield potential (YP) under defined growth conditions without biotic or abiotic stress [37,38]. The model has been used widely in the USA [39] and China [40,41]. The spring maize YPs in 2015 and 2016 were estimated based on meteorological data (e.g., solar radiation, precipitation, and maximum and minimum temperatures), sowing date, planting density, hybrid maturity, bulk density, and other factors [38]. The simulated YPs and biomasses were 14.6 and 24.8 Mg ha⁻¹ in 2015, and 15.8 and 25.3 Mg ha⁻¹ in 2016, respectively.

2.6. Economic Analysis

Economic analysis was carried out using the partial budgeting method [21] and had two main components: Variable input and yield gain. The variable input per hectare excluded common inputs (e.g., seeds, fertilizer, and irrigation water).

$$\text{Economic return} = \text{yield gain} - \text{variable input}. \quad (1)$$

$$\text{Yield gain} = \text{grain yield} \times \text{maize grain price (0.24 \$ kg}^{-1}\text{)}. \quad (2)$$

$$\text{Variable input} = \text{material (141 \$ ha}^{-1}\text{)} + \text{traffic transport (120)} + \text{labor service (72.5)}. \quad (3)$$

2.7. Statistical Analysis

The effects of year, salinity level, and treatment on the yield, ear number, grains per ear, and grain weight were evaluated by three-way analysis of variance (ANOVA) using the statistical analysis system (SAS Institute, 1998; Cary, NC, USA). One-way ANOVA was used to analyze the effects of treatment on biomass and ion accumulation in maize, as well as soil properties (pH and SOC, Ca²⁺, and Na⁺ contents). Following an *F* test, multiple comparison of means (*p* < 0.05) was conducted with Fisher's protected least significant difference.

3. Results

3.1. Simulated Yield Potential, Grain Yield, and Economic Return

The model-simulated YPs for maize were 14.6 Mg ha⁻¹ in 2015 and 15.8 Mg ha⁻¹ in 2016. These YPs were similar to those in other regions of China [41]. The control treatments in both years achieved 38.2%–49.9% of the YP at the moderate salinity level and 14.0%–28.0% of the YP at the high salinity level. The CA treatment increased yields to 51.6%–52.6% of the YP at the moderate salinity level and 29.0%–42.9% of the YP at the high salinity level (Table 2).

Grain yield and yield components were significantly affected by year, salinity levels, and treatment except for year on the grains per ear (Table 3). Over both years, maize yields with the CA treatment were 17.7% and 70.2% higher than the control at the moderate and high salinity levels, respectively (Table 2). The large increase in yield associated with CA treatment was attributed to increased ear number, grain number, and grain weight at the high salinity level. In contrast, CA treatment significantly increased only the grain number per ear at the moderate salinity level. Higher maize yields across all treatments and salinity levels were observed in 2016 compared with 2015 because of the higher ear number (Table 2).

Table 2. Maize yield, yield components, and economic return with different treatments (control and CA), salinity levels (moderate and high salinity levels), and year (2015 and 2016).

	Yield (Mg ha ⁻¹)	The Ratio of YP (%)	Ear Number (10 ⁴ ha ⁻¹)	Grain Number per Ear	Grain Weight (g 1000 ⁻¹)	Economic Return (\$ ha ⁻¹)
2015 Moderate						
control	5.58	38.2	6.42	420	269	1351
CA	7.53	51.6	6.56	528	283	1489
LSD _{0.05}	1.51		ns	48.2	ns	
2015 High						
control	2.05	14.0	4.25	329	207	496.2
CA	4.23	29.0	5.94	451	264	690.3
LSD _{0.05}	2.08		1.11	121	33.3	
2016 Moderate						
control	7.88	49.9	7.73	400	295	1907
CA	8.31	52.6	7.96	508	290	1678
LSD _{0.05}	0.42		ns	50.4	ns	
2016 High						
control	4.42	28.0	5.86	304	230	1070
CA	6.78	42.9	8.06	401	281	1307
LSD _{0.05}	1.61		1.63	96.4	37.9	

CA and control indicate the combination and control treatments, respectively; the ratio of YP (yield potential) = yield/YP.

Table 3. Maize yield and yield components as affected by treatments, salinity levels, and year. All data for the ANOVA come from Table 2.

ANOVA	Sum of Squares	Degrees of Freedom	Mean of the Squares	F Value	p Value
Yield (Mg ha ⁻¹)					
Year	24.018	1.000	24.018	52.70	<0.0001
Salinity levels	52.330	1.000	52.330	114.82	<0.0001
Treatment	17.943	1.000	17.943	39.37	<0.0001
Ear number (10 ⁴ ha ⁻¹)					
Year	15.589	1.000	15.589	66.68	<0.0001
Salinity levels	7.772	1.000	7.772	33.24	<0.0001
Treatment	6.793	1.000	6.793	29.06	<0.0001
Grains per ear					
Year	5097.7	1.000	5097.7	3.64	0.0744
Salinity levels	51729	1.000	51729	36.98	<0.0001
Treatment	70790	1.000	70790	50.60	<0.0001
Grain weight (g 1000 ⁻¹)					
Year	2070.2	1.000	2070.2	6.32	0.0231
Salinity levels	9067.6	1.000	9067.6	27.66	<0.0001
Treatment	4987.2	1.000	4987.2	15.22	0.0013

Compared with the control, the CA treatment increased grain yield income by 17.7%, but decreased the economic return by 45.0 \$ ha⁻¹ at the moderate salinity level because of high variable input. In contrast, the CA treatment achieved a 70.2% increase in grain yield income and a 215 \$ ha⁻¹ gain in economic return at the high salinity level (Table 2).

3.2. Simulated and Experimental Biomass Accumulation

Averaged over both years, the simulated biomass at maturity was 25.0 Mg ha⁻¹. Experimental biomasses were 36.7% of the simulated biomass under the control condition and 52.8% of the simulated biomass under CA treatment (Figure 2).

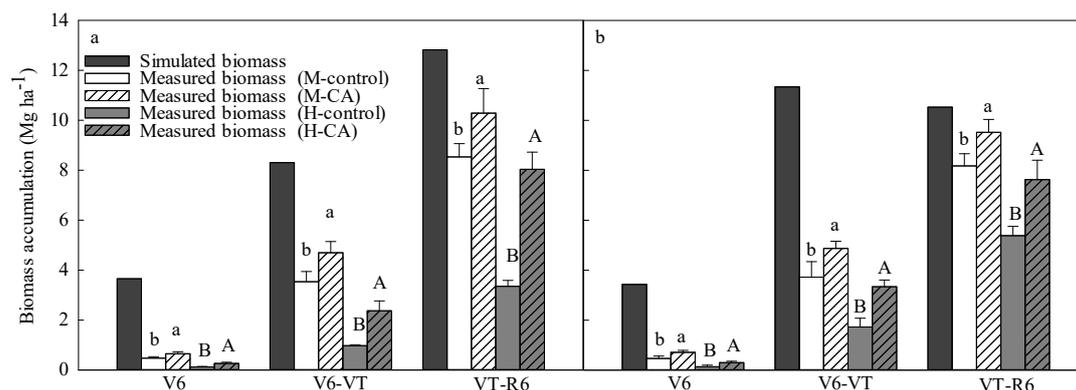


Figure 2. Simulated and measured biomass accumulation with different treatment (control and CA) in 2015 (a) and 2016 (b) during different growth stages. M-control and M-CA was in moderate salinity level. H-control and H-CA was in high salinity level. V6, V6-VT, and VT-R6 were represented for six-leaf stage, from six-leaf stage to tassell stage, and tasseling to mature stage, respectively. Values with the same salinity level, year, and stage followed by the different letters (a and b, A and B) do differ significantly from each other ($p < 0.05$).

Biomass accumulation at maturity increased by averages of 2.91 and 5.12 Mg ha⁻¹ under the CA treatment compared with the control at the moderate and high salinity levels, respectively. Of these total increases, 7.21% and 2.95% could be attributed to the V6 stage, 39.6% and 29.3% to the V6–VT stage, and 53.2% and 67.7% to the VT–R6 stage, respectively (Figure 2). These observations indicated that the increased biomass accumulated mainly during the late growth stages of maize, especially at the high salinity level.

At the V6 stage, the biomass accumulation for the CA treatment was 44.7% (V6: 0.68 Mg ha⁻¹) greater than that of the control at the moderate salinity level, and 118% (V6: 0.28 Mg ha⁻¹) greater than that of the control at the high salinity level. From the V6 to the VT stage, CA treatment increased biomass accumulation by 31.8% (V6-VT: 4.78 Mg ha⁻¹) and 111% (V6-VT: 2.85 Mg ha⁻¹) at the moderate and high salinity levels, respectively. The greatest biomass accumulation in the CA treatment groups occurred at the VT–R6 stage (VT–R6: 9.90 and 7.84 Mg ha⁻¹, respectively), and were 18.5% and 79.4% higher, respectively, than those in the control.

3.3. Ion Contents of Maize

The contents of ions (N, P, K, Ca, Mg, and Na) in maize at maturity were affected significantly by the treatment, salinity level, and year (with the exception of N and K, which were not affected by year; Figure 3). At the high salinity level, the contents of N, P, K, Ca, and Mg under the CA treatment increased significantly, by 35.9%–160%, whereas Na content was reduced by 25.3%–49.3% compared with the control. This decrease in Na content may be attributed to significant reductions in the Na concentration (62.5%–71.4%) and increases in biomass accumulation (55.5%–140%). At the moderate salinity level, the CA treatment significantly increased N, P, K, Ca, and Mg contents, by 20.3%–76.5%, and reduced Na content by 27.7%–32.2% compared with the control, except for N and P in 2016. The low Na content could be explained by significant reductions in the Na concentration (38.2%–53.5%) and increases in biomass accumulation (22.1%–24.6%).

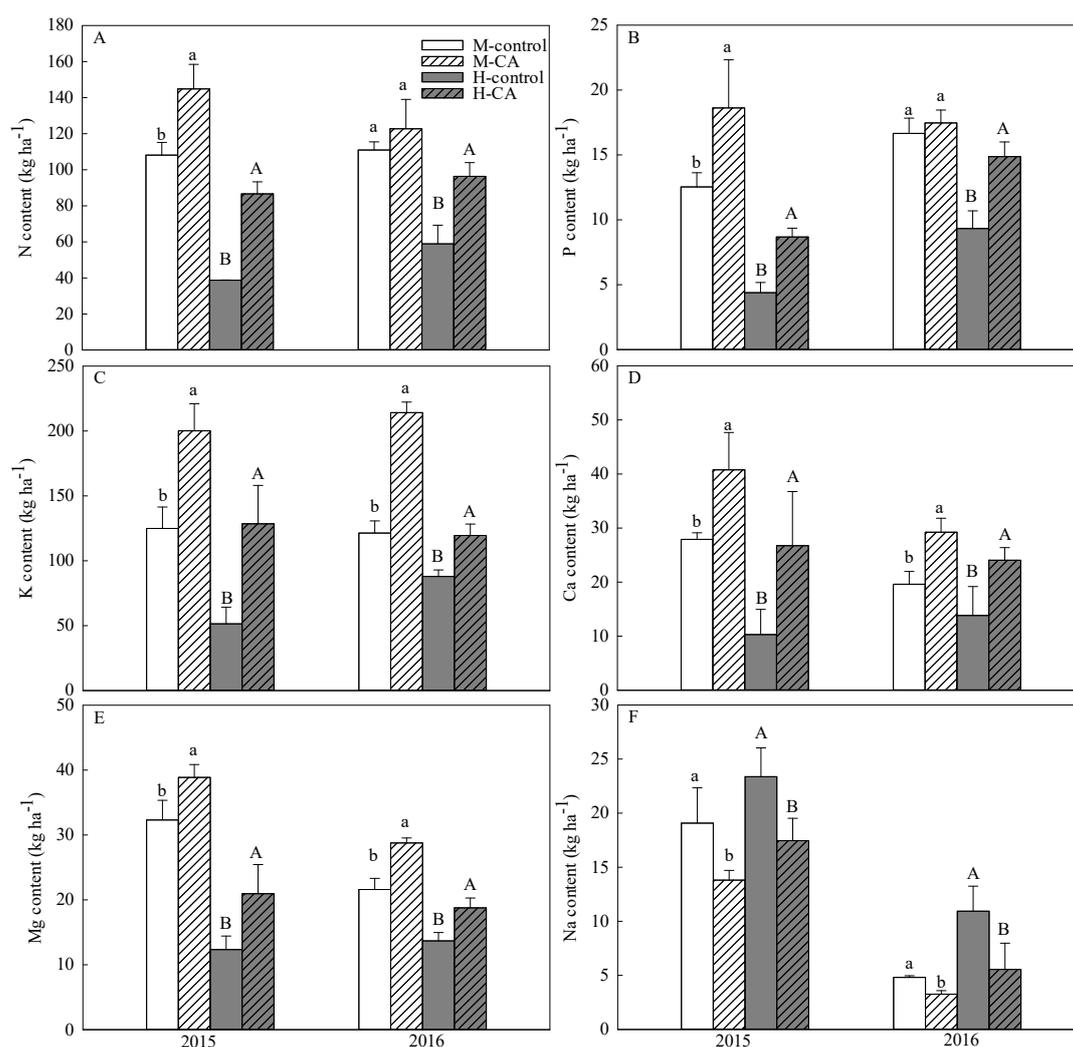


Figure 3. Contents of N, P, K, Ca, Mg, and Na at maturity with different treatment (control and CA) and salinity levels in 2015 and 2016. (A–F) represent the contents of N, P, K, Ca, Mg, Na. M-control and M-CA was in moderate salinity level. H-control and H-CA was in high salinity level. Values with the same salinity level, year, and stage followed by the different letters (a and b, A and B) do differ significantly from each other ($p < 0.05$).

3.4. Soil Properties

The soil pH in the 0–20 cm soil layer decreased significantly under the CA treatment, by 0.09 and 0.07 compared with the control at the moderate and high salinity levels, respectively. Soil pH in the 20–40 cm soil layer decreased by 0.11 at the moderate salinity level, but did not change significantly at the high salinity level (Table 4).

SOC contents in the 0–20 cm soil layer under the CA treatment were 14.1% and 23.4% higher than the control at the moderate and high salinity levels, respectively. The SOC content increased by 43.1% in the 20–40 cm soil layer at the high salinity level, but did not change significantly at the moderate salinity level (Table 4).

The CA treatment increased the soil Ca²⁺ content by 12.8% and 21.3% compared with the initial value and by 28.1% and 22.7% compared with the control in the 0–20 cm soil layer at the moderate and high salinity levels, respectively. No significant difference was observed the 20–40 cm soil layer, except at the high salinity level. The CA treatment reduced soil Na⁺ contents by 53.5% and 34.1% in the 0–20 and 20–40 cm soil layers, respectively, at the high salinity level. No significant difference was observed at the moderate salinity level (Table 1; Table 4).

Table 4. Soil pH, soil organic carbon (SOC), soil Ca²⁺, and Na⁺ contents in different soil layers with different treatments (control and CA), and salinity levels (moderate and high) at post-harvest in 2016.

	Soil pH		SOC (g kg ⁻¹)		Soil Ca ²⁺ (g kg ⁻¹)		Soil Na ⁺ (g kg ⁻¹)	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Moderate								
control	8.17	8.23	5.05	2.52	3.31	3.04	0.46	0.29
CA	8.08	8.12	5.76	2.46	4.24	3.08	0.38	0.25
LSD _{0.05}	0.06	0.08	0.64	ns	0.15	ns	ns	ns
High								
control	8.33	8.33	3.93	1.97	3.53	2.97	1.42	0.82
CA	8.26	8.29	4.85	2.82	4.33	3.29	0.66	0.54
LSD _{0.05}	0.05	ns	0.86	0.59	0.26	0.27	0.23	0.23

ns, not significant.

4. Discussion

The control treatment, which reflected current farming practices, achieved only 44.1% and 21.0% of the YPs at the moderate and high salinity levels, respectively, indicating that significant yield improvement should be possible. Maize yields increased to 52.1% and 36.0% of the YP under the CA treatment at the moderate and high salinity levels, respectively, supporting the hypothesis that CA treatment could mitigate salt damage from osmotic stress and ionic toxicity, increasing maize yield.

During the early growth stages, the CA treatment improved the emergence rate and ear number and increased biomass accumulation compared with the control, and these effects were stronger at the high salinity level. As a mechanistic explanation for these improvements, the CA treatment may have decreased soil salts due to the application of FGDC, decreased osmotic stress, and improved maize growth [15,16,42]. Previous reports also indicated that FGDC could improve saline–sodic soil and increase the maize emergence rate and shoot dry weight, and that these effects were stronger at higher soil salinity level [13,43].

Maize was more susceptible to soil salinity during the vegetative stages, especially in the later growth stages [44,45]. The CA treatment increased biomass accumulation from the V6 to VT stage, resulting in 26.3% and 34.6% increases in grain number per ear at the moderate and high salinity levels, respectively. Increasing biomass accumulation during the growth phase is essential to achieve high grain numbers [46,47].

During the reproductive growth stages, the CA treatment increased the Ca content in maize; improved cell membrane selectivity to K and Na, leading to reduced Na accumulation; caused more N, P, K, and Mg accumulation [21]; mitigated the harmful effects of ionic imbalance on maize growth [16]; and thereby increased biomass accumulation from VT to R6. Reduced Na accumulation under the CA treatment also slowed the senescence of transpiring leaves [17] and promoted the transport and accumulation of essential nutrients from other organs to harvestable organs [48]. These processes resulted in high grain weights and grain yields, especially at the high salinity level, because these parameters are determined mainly by nutrient and biomass accumulation from silking to maturity [47,49,50].

Our results also support the hypothesis that the CA treatment would substantially improve soil properties. The CA treatment increased the SOC content and decreased the soil pH, which can be explained by FR's rich organic matter content and acidity (pH 3.3). Previous studies showed that FR promotes the formation of flocculation and massive soil aggregates [24,51]. As FR is an acidic and organic material, its decomposition releases additional hydrogen (H⁺) to reduce soil pH when added to soil [24]. In addition, FGDC increases Ca²⁺ levels, resulting in calcite precipitation and H⁺ release [21]. The CA treatment reduced the Na⁺ content and increased the Ca²⁺ content in the top soil layer because FGDC supplies Ca²⁺ to replace Na⁺ in clay, which improved soil Na⁺ leaching out of the root zone [23,42]. These effects were more obvious at the high salinity level. The post-harvest bulk

density in 2016 was similar between the CA treatment and the control in the present study (data not shown), although other studies have shown that FGDG application slightly increased bulk density and weakened soil aggregate stability [25,27]. This observation may be partly explained by the short-term addition of FR and straw return in this study.

The yield gains for maize grown in coastal saline soil after combined FGDG and FR application were striking; however, the CA treatment increased the yield only to 44.2% of the YP (compared with 32.6% of the YP for the control). We believe that soil improvement efforts over a longer time period and the integration of other management practices (e.g., the use of optimal hybrids and crop management techniques) will help to close the yield gap further. However, this approach has several limitations, such as the large amendment dose required and the lack of mechanized operation in the coastal region of northern China, resulting in a high cost. The economic return under the CA treatment was lower than that of the control at the moderate salinity level, but higher at the high salinity level because of increased yield. However, most farmers perceive little incentive to adopt this technology because of labor limitations and small typical land areas (<0.5 ha per farmer) [52,53]. In the future, other factors may encourage farmers to adopt this technology, including the implementation of regulatory policies (e.g., subsidies), the development of more economically viable and complete systems (e.g., mechanization), and further increases in grain yield and resource use efficiency in combination with other improvement measures (e.g., tillage and mulching). Although some studies showed that the massive of FGDG and FR did not result in soil contamination in short or long term measurement [24,51], we still need to carry out further research on soil contamination.

5. Conclusions

CA treatment significantly reduced gaps in maize yield and biomass, and these effects were stronger at the high salinity level. In the 0–20 cm soil layer, the CA treatment increased the Ca^{2+} and SOC contents and decreased the soil pH and Na^+ content. Due to the growing population and increasing stresses on food production, the utilization of land with soil constraints as efficiently as possible is becoming more important. Soil improvement efforts will result in large gains in grain output, ensuring greater profits for farmers and better food security.

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