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Inorganic improver and straw returning promote corn growth and improve the quality of saline soils

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Abstract: Soil salinisation is a major constraint on food security and agricultural development, and remains a critical concern in the agricultural sector. In this study, we examined the effects of three straw return methods – straw mulching, straw burial, and a combination of straw mulching and burial – along with inorganic amendments ($CaSiO_3$ and $MgSO_4$) on maize growth, soil organic matter, bulk density, salinity, and the contents of individual salt base ions. A 120-day planting experiment was conducted using soil columns and included maize cultivation under irrigation and drenching conditions. The combined treatments (straw return with Ca-Mg application) were more effective in reducing salinity and improving soil properties than straw return alone. Na^+, K^+, Cl^-, and HCO_3^- contents, as well as soil bulk density, decreased by 45.99–48.43, 28.07–28.36, 20.91–24.17, 18.93–21.03, and 7.64–8.40%, respectively. Regarding crop growth promotion, compared with the single treatment, the combined application of straw return with Ca-Mg (PI, SPI) resulted in a 6.46–8.30% increase in superoxide dismutase activity, an 8.66–10.83% reduction in malondialdehyde content, a 12.71–22.70% increase in total root length, a 13.41–24.14% increase in root surface area, and a 12.46–19.02% increase in root volume. Taken together, integrating straw return with a calcium-magnesium mixture represents a promising strategy for improving the quality of coastal saline soils.

Keywords: abiotic stress; soil quality; desalination; soil salt reduction; soil modification

Soil salinisation, one of the major factors contributing to the decline in crop yield, has garnered increasing attention in recent years within the agricultural sector worldwide (Xiao et al. 2024). The global area of saline soils is approximately 9.55×10^8 ha, accounting for 10% of the total land area (Wang et al. 2023). Notably, the total area of saline soil in China exceeds $3\,600 \times 10^4$ km^2, particularly in the coastal plains of the Bohai Sea, Yellow Sea, and East China Sea, which collectively cover 5×10^5 ha (Fei et al. 2024). Due to the high salt content, poor soil structure, and low fertility of these soils (Qi et al. 2023, Fang et al. 2024), plant growth is considerably inhibited, physiological metabolism is disrupted, crop quality deteriorates, and, in severe cases, plant death occurs (Nan et al. 2016, Liu et al. 2019). Therefore, there is an urgent need to improve soil quality, which is a crucial strategy for constructing a national ecological civilisation and safeguarding the ecological environment. Furthermore, enhancing soil quality is essential for achieving high-quality agricultural development and ensuring national food security (Yao et al. 2024).

Straw returning, a common agricultural management practice, reduces evaporation, inhibits salt accumulation, and promotes the downward migration of salts. Additionally, it acts as an organic cementing

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material, facilitating the formation of soil aggregates, improving soil structure, and enhancing soil fertility (Cheng et al. 2024). Qi et al. (2023) reported that straw returning to the field increased the desalination rate of saline soils to 45%, effectively raised soil organic carbon content by 19%, and boosted crop yield by approximately 12%. Chen et al. (2023) found that deep straw burial improved soil structure, reduced soil bulk density by 24%, and increased crop yield by 17%. Similarly, Huang et al. (2024) observed that organic carbon and other nutrient contents in the soil increased by 22.4% following straw incorporation. Zhang et al. (2024a) demonstrated that straw returning effectively reduced soil bulk density by 17.8%, thereby improving the soil tillage environment, promoting root growth, increasing maize root length by 21.2% and root area by 17.7%, and delaying root senescence. Furthermore, Xu et al. (2024) concluded that various straw-returning methods promoted maize growth and development while increasing yield, with deep straw returning proving the most effective, leading to a 15.9% increase in yield – significantly higher than the 9.2% increase achieved through straw mulching alone. Zhang et al.(2023) further determined that deep straw returning effectively mitigated the adverse effects of salinity stress on crops through physiological and biochemical pathways, promoting crop growth and development. This method also reduced malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) contents by 12.7–16.4% while increasing peroxidase (POD) and superoxide dismutase (SOD) activities by 17–23%. However, whether the combination of straw mulching and straw burial is more effective than either method alone remains unclear, and its underlying mechanism has yet to be fully elucidated.

Calcium (Ca) and magnesium (Mg) have also been recognised as inorganic binding materials for soil aggregate formation (Ahmed et al. 2024). Application of Ca and Mg can facilitate the exchange of salt-based ions in the soil through chemical interactions, increase the Ca^{2+} and Mg^{2+} contents required for plant growth, reduce Na^+, Cl^-, and HCO_3^- contents, and promote salt leaching (Song et al. 2024). Moreover, it improves the soil's physicochemical properties, enhances soil organic carbon content, and promotes plant growth. The application of $CaSiO_3$, through its drenching effect, can reduce soil pH by 1.06 and decrease soil alkalinity by 14.13–20.64%, significantly improving the availability of nitrogen, phosphorus, and potassium in the soil while enhancing organic carbon content by 8–10.4%. This, in turn, disrupts soil platelets and improves both soil permeability and water infiltration (Gui et al. 2024).

Meanwhile, the application of chemical materials containing Mg^{2+} and SO_4^{2-} reduced soil salinity by 17–28%, while CO_3^{2-} and HCO_3^- contents decreased by 22.4% and 20.8%, respectively, with the increase in SO_4^{2-} (Elmeknassi et al. 2024). Additionally, Ajmeri et al. (2024) concluded that soil conditions became more favourable for plant root growth and development following the application of inorganic additives, leading to significant improvements in root morphometric indicators, such as the number of root tips, root length, root surface area, and root volume, including a 30–35% increase in root length and a 25–30% increase in volume. Moreover, inorganic amendments can also reduce oxidative stress by increasing antioxidant enzyme activities (SOD, POD, etc.) in plants. These enzymes play a crucial role in scavenging free radicals and peroxides, thereby reducing the accumulation of harmful substances such as MDA and H_2O_2 and increasing the plant's antioxidant resistance by more than 25% (Łukowiak et al. 2024). Therefore, the combination of Ca^{2+}, Mg^{2+}, and SO_4^{2-} may benefit soil structure, ionic equilibrium, and plant growth. Further research is needed to elucidate the mechanisms underlying these enhancements.

Generally, current technology for saline soil improvement and utilisation is predominantly based on single approaches, with related research primarily focusing on comparisons of various straw return methods, return amounts, or the screening of inorganic amendment materials and their dosages. However, few studies have examined the effects of straw return combined with chemical amendments on salt reduction, soil improvement, fertility enhancement, and plant growth promotion.

We hypothesised that an effective straw return method, coupled with inorganic amendments ($CaSiO_3$ and $MgSO_4$), is a preferable approach for enhancing soil nutrients and structure, achieving greater salt reduction and soil reformation, and ultimately promoting plant growth compared to any single treatment. Therefore, this study focused on improving salinised soils in the Bohai Economic Circle by investigating soil salt reduction, soil modification, and crop growth promotion. Specifically, it examined the effects of different straw return methods and their combined application with inorganic amendments on salt reduction, soil modification, and maize growth in saline soils.

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These findings will help clarify the effects of multiple combined measures, contribute to the development of a comprehensive soil improvement technology for coastal saline soils, and enrich the theoretical understanding of organic-inorganic composite technology for saline-alkali land improvement.

MATERIAL AND METHODS

Experimental materials

Soil samples were collected from the "Bohai Grain Silo Demonstration Area" (Longitude: approximately 117°54'–117°56'E, Latitude: approximately 37°54'–37°57'N) in Wudi County, Binzhou City, Shandong Province, China. The soil type was Solonchaks, and pH was 8.40 and cation exchange capacity (CEC) was 9.6 cmol/kg. The soil salinity was 2.08% in the 0–20 cm layer, 3.36% in the 20–40 cm layer, and 3.88% in the 40–60 cm layer. Laminated sampling was conducted.

The organic carbon content of the soil was 6.54 g/kg, the available P content was 7.83 mg/kg, and the available K content was 312.11 mg/kg. The soil bulk density was 1.42 g/cm^3. The concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+, SO_4^{2-}, Cl^-, and HCO_3^- were 1.55, 0.66, 0.44, 8.60, 1.61, 0.3, and 0.057 g/kg, respectively. The soil column was a customised PVC pipe with a diameter of 25 cm and a height of 70 cm. Straws were collected from farmland in the Taishan District, Tai'an City, Shandong Province, China. The inorganic amendments used included a mixture of calcium and magnesium, with $CaSiO_3$ and $MgSO_4$ as the primary components. Both were of analytical grade and purchased from Sinopharm Chemical Reagent (Shanghai, China).

Experimental design

The soil was layered into customised PVC pipes and filled in layers according to its bulk density. The following seven treatments were established: S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver, and SPI – straw mulching + straw burial return + inorganic improver. The experiment was conducted in a glasshouse at the Experimental Station of Shandong Agricultural University (117°15'E, 36°17'N); each treatment was replicated thrice.

Straw was crushed to approximately 2–5 cm length and either mixed into the 0–20 cm soil layer or applied as mulch at a rate of 3 600 kg/ha. In the straw mulching + burial return treatment, the straw was applied in a 1:2 ratio (mulching:burial), ensuring a consistent total straw application across all straw return methods.

Inorganic improvers were incorporated into the 0–20 cm soil layer at a rate of 1.82 g calcium silicate ($CaSiO_3$) and 3.12 g anhydrous magnesium sulphate ($MgSO_4$). Each soil column received 1.104, 0.324, and 0.305 g of N, P, and K, respectively, mixed into the 0–20 cm soil layer.

Maize was planted in April 2021, with five plants per soil column, and harvested in August 2021, resulting in a total growing period of 120 days.

Analytical methods

Soil indicators. Soil water-soluble salt content and the concentration of each salt radical ion were determined using the method described by Soukehal et al. (2024). A 5:1 water-to-soil ratio was used to extract and filter the soil solution for testing. HCO_3^- was determined by neutralisation titration with two indicators, SO_4^{2-} was measured using barium sulphate turbidimetry, and Cl^- was analysed by $AgNO_3$ titration. Ca^{2+} and Mg^{2+} were quantified using atomic absorption spectrophotometry (JC-YZXS-400B, Nanjing, China), while Na^+ and K^+ were determined by flame photometry (YT-20, Shenzhen, China). The total soil water-soluble salt content was measured using the dried residue method (soil-to-water ratio 1:5).

Soil organic carbon was determined by the volumetric method with potassium dichromate and external heating, while bulk density was measured using the ring knife method.

Determination of plant Na^+, Ca^{2+}, Mg^{2+}. Plant salt ion content was determined using the method described by Nur et al. (2025). Ca^{2+} and Mg^2 were quantified using atomic absorption spectrophotometry (JC-YZXS-400B), while Na^+ was measured by flame photometry (YT-20).

Plant nutrient determination

Plant N, P, and K contents were determined following the method described by Nur et al. (2025). Total nitrogen was measured using the Kjeldahl method, total phosphorus using the vanadium-molybdenum yellow colourimetric method, and total potassium using flame photometry.

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Plant root conformation and physiological indicators

Plant root conformation and physiological indicators were determined following the method described by Qin et al. (2024). The roots were laid flat in a root tray containing a small amount of deionised water and scanned using a Nakajima Scanmaker i800 Plus scanner (Shanghai, China) to record root morphology. Subsequently, root conformation was analysed using the Wanshen LA-S Plant Root Analysis System (Hangzhou, China).

MDA, H_2O_2, POD, and SOD contents were determined using the A003-1, A064-1, A084-3, and A001-1 kits (Nanjing Jiancheng Bioengineering Institute, Nanjing, China), respectively. Suitable plant parts were selected, gently rinsed with distilled or deionised water to remove surface dust and contaminants and placed in liquid nitrogen immediately for quick freezing to stop enzyme activity and metabolic reactions. The steps listed in the protocol provided with the kit were strictly followed; plant tissue samples were briefly taken, different extracts were added, and the samples were homogenised in an ice bath. After centrifugation, the supernatant was collected for further analysis.

The absorbance for the MDA assay was measured at 532 nm and 600 nm after cooling. For the H_2O_2 assay, the absorbance was measured at 410 nm. The supernatant was mixed with guaiacol and H_2O_2 for the POD assay, and the absorbance was measured at 470 nm over time. For the SOD assay, absorbance was measured at 560 nm over time.

Statistical analysis

Data were graphically presented using Origin 2019 (OriginLab Corporation, Massachusetts, USA). SPSS (version 21.0, IBM, New York, USA) was used for statistical analyses. The datasets were subjected to ANOVA, and significantly different mean values were identified using Duncan's multiple range test, with statistical significance set at $P < 0.05$.

RESULTS

Soil salt content

Soil total salt content. Total soil salt content was significantly reduced by straw return or inorganic improver application (Figure 1), with a 31.59–43.22% decrease ($P < 0.05$) relative to CK. No significant differences were observed in total salt content among the S, P, and SP treatments. Similar total salt contents were detected between P and PI, as well as between SP and SPI.

The total soil salt content in the S, P, and SP treatments was reduced by 39.26–43.22% ($P < 0.05$) compared with the CK treatment, whereas in the I, PI, and SPI treatments, it was reduced by 31.59–34.14% ($P < 0.05$) compared with the CK treatment.

Soil cation content (K^+, Na^+, Ca^{2+} and Mg^{2+}). Soil Na^+ and K^+ contents were significantly reduced by straw return and inorganic improver application (Figure 2). The soil Na^+ contents under the S, P, and SP treatments were significantly lower ($P < 0.05$), with a reduction of 16.70, 30.26, and 35.26%, respectively, than those under CK. Similarly, the I, PI, and SPI treatments resulted in 59.72, 64.04, and 65.04% reduction, respectively. No significant differences were observed in soil K^+ content among the S, P, and SP treatments compared with those under the CK treatment. However, the I, PI, and SPI treatments caused 22.61, 30.94, and 34.00% reduction, respectively, ($P < 0.05$) compared to CK. The I treatment resulted in a significant reduction of 37.77–51.64% in Na^+ and 15.66–19.72% in K^+ contents ($P < 0.05$) when compared with the S, P, and SP treatments. Compared to P, the PI treatment led to a significant reduction ($P < 0.05$) of 48.43% in Na^+ content and 28.36% in K^+ content. Similarly, the SPI treatment resulted in a significant reduction ($P < 0.05$) of 45.99% in Na^+

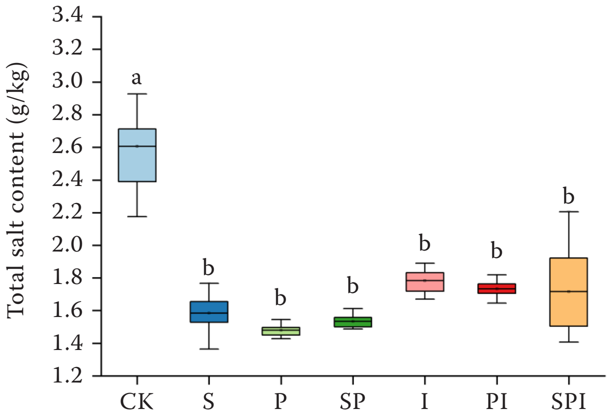

Figure 1. Total salt content of tillage soil under different treatments. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

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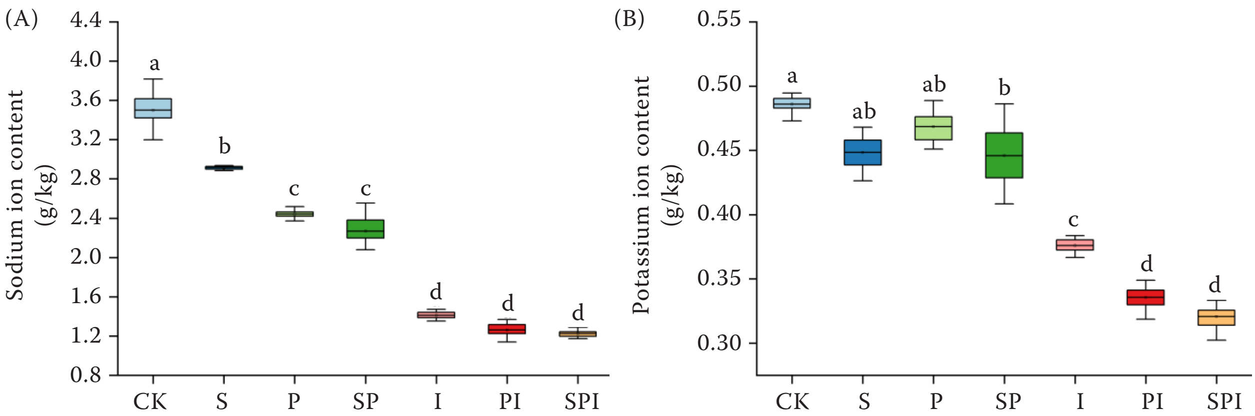

Figure 2. (A) Sodium and (B) potassium ion contents of the tillage soil under different treatments. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences (P < 0.05) among treatments

content and 28.07% in K^+ content when compared with the SP treatment. Compared with the I treatment, the PI and SPI treatments caused a significant reduction in soil K^+ content (P < 0.05) (10.77% and 14.72%, respectively).

Soil Ca^{2+} and Mg^{2+} contents significantly increased after inorganic improver application (Figure 3), with the I, PI, and SPI treatments resulting in an increase (P < 0.05) of 25.91, 26.31, and 26.88%, respectively, in Ca^{2+} content and 12.65, 14.11, and 16.13%, respectively, in Mg^{2+} content relative to that under CK. No significant differences were observed in Ca^{2+} and Mg^{2+} contents among the S, P, and SP treatments or among the I, PI, and SPI treatments. The I treatment resulted in a 23.45–26.34% increase in Ca^{2+} content and a 16.05–20.44% increase in Mg^{2+} content (P < 0.05) compared to the S, P, and SP treatments. The PI treatment significantly increased (P < 0.05) Ca^{2+} and Mg^{2+} contents by 26.74% and 17.45%, respectively, compared with the P treatment. Similarly, the SPI treatment significantly increased (P < 0.05) Ca^{2+} and Mg^{2+} contents by 24.45% and, 23.61%, respectively, compared with the SP treatment.

Soil anion contents (Cl^-, HCO_3^-, and SO_4^{2-}). No significant differences were observed in the soil Cl^-, SO_4^{2-}, and HCO_3^- contents under the S, P, and SP treatments compared with those under the CK treatment (Figure 4). The I, PI, and SPI treatments

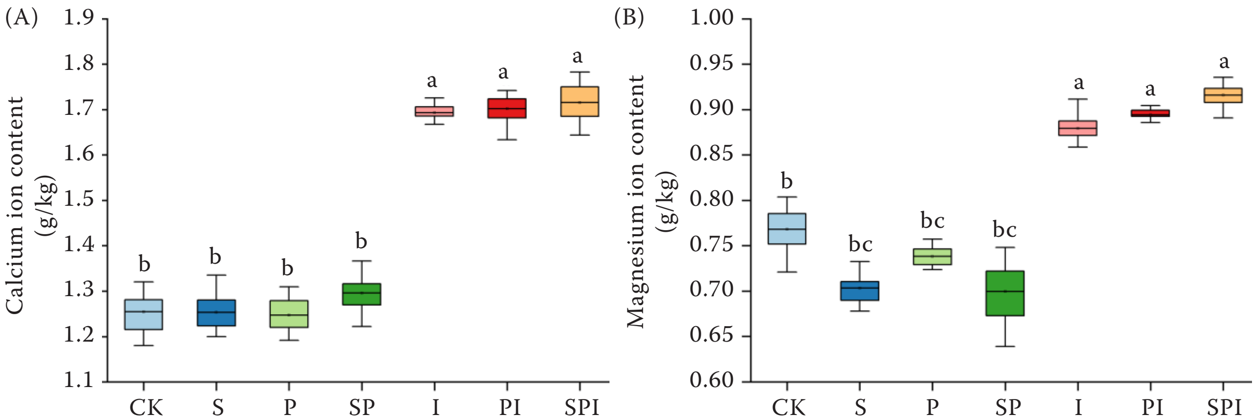

Figure 3. (A) Calcium and (B) magnesium ion contents of the tillage soil under different treatments. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences (P < 0.05) among treatments

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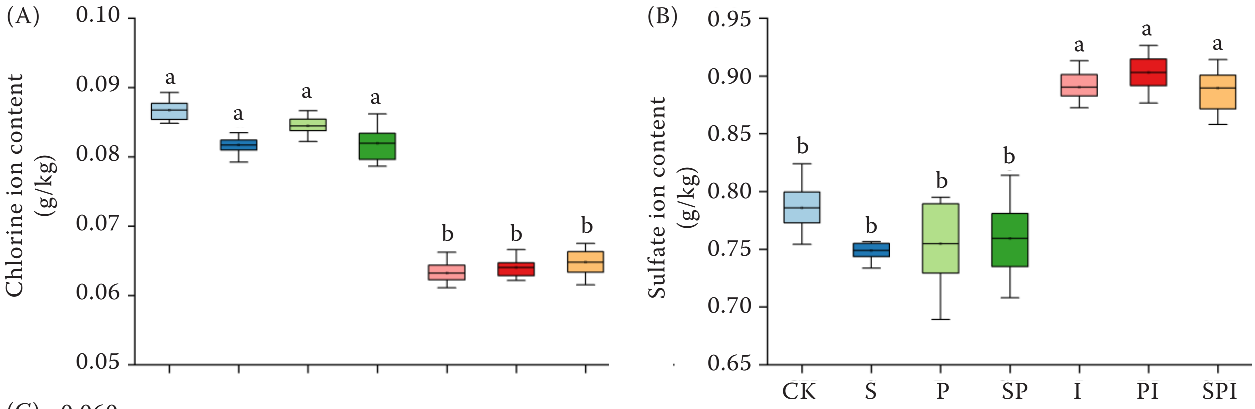

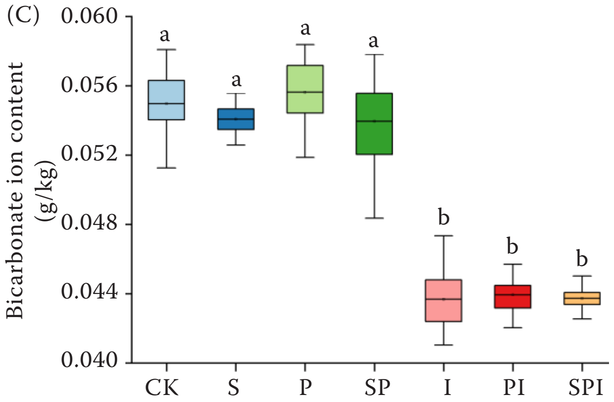

Figure 4. (A) Chloride; (B) sulphate, and (C) bicarbonate ion contents of the tillage soil. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

significantly decreased ($P < 0.05$) Cl^- content by 25.29–27.12% and HCO_3^- content by 20.08–20.54%. Furthermore, these treatments caused a significant increase of 11.66–12.96% ($P < 0.05$) in SO_4^{2-} content compared to CK.

The I treatment caused a significant ($P < 0.05$) decrease of 22.61–25.13% in Cl^- content and 19.05–21.49% in HCO_3^- content while increasing SO_4^{2-} content by 14.71–15.89% relative to the S, P, and SP treatments. Compared with the P treatment, PI significantly ($P < 0.05$) reduced Cl^- content by 24.17% and HCO_3^- content by 21.03% while increasing SO_4^{2-} content by 16.42%. Compared with the SP treatment, SPI significantly ($P < 0.05$) reduced Cl^- content by 20.91% and HCO_3^- content by 18.93% while increasing SO_4^{2-} content by 14.64%.

Soil organic carbon content. Straw return significantly increased soil organic carbon content (Figure 5), with the S, P, and SP treatments resulting in an increase of 11.95, 16.40, and 19.40% ($P < 0.05$), respectively, relative to CK. The PI and SPI treatments increased by 17.56% and 22.49% ($P < 0.05$), respectively, compared with CK, while no significant difference was observed under the I treatment relative to that under CK. Similar organic carbon contents were observed under the P and PI treatments as well as under SP and SPI. No significant differences in organic carbon content were observed among the S, P, SP, PI, and SPI treatments.

Soil bulk weight. Straw return or inorganic improver application significantly reduced soil bulk density (Figure 6), with a 10.80–22.11% decrease

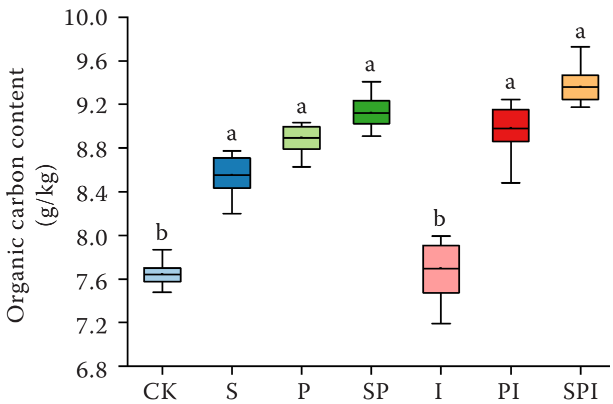

Figure 5. Organic carbon content of the tillage soil. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

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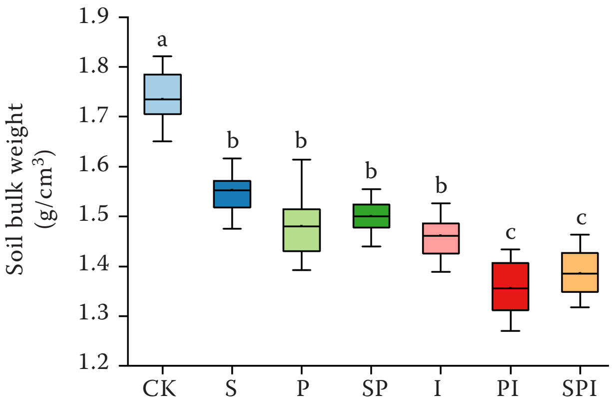

Figure 6. Bulk density of the tillage soil. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

($P < 0.05$) relative to that under CK. No significant differences were observed among the S, P, and SP treatments or among the I, PI, and SPI treatments. The PI treatment significantly reduced ($P < 0.05$) bulk density by 8.40% compared with the P treatment, while the SPI treatment significantly reduced ($P < 0.05$) bulk density by 7.64% compared with the SP treatment. Additionally, the PI and SPI treatments significantly reduced ($P < 0.05$) bulk density by 7.17% and 5.10%, respectively, compared with the I treatment.

Plant cation contents (Na^+, Ca^{2+}, and Mg^{2+})

Na^+ was the most dominant toxic ion inhibiting plant growth; the test results indicated that Na^+ content in the plants followed the trend: roots > stems > leaves (Figure 7). Na^+ content in the stems was significantly reduced ($P < 0.05$) by 23.66–35.53% compared with that under CK, under most treatments, except for the SP and I treatments. Similarly, the Na^+ content of leaves was significantly reduced ($P < 0.05$) by 41.68–88.90% under all treatments, except for I, compared with that under CK.

Some variability was observed in Ca^{2+} and Mg^{2+} contents (Figure 8) among the treatments at the maturity stage. Overall, Ca^{2+} and Mg^{2+} contents in the plants exhibited the following trend: leaves > stems > roots. No significant differences in Ca^{2+} and Mg^{2+} contents in the S, P, and SP treatments compared with CK were observed.

The I, PI, and SPI treatments increased the Ca^{2+} content by 64.79, 65.78, and 65.88% in the roots, by 32.35, 39.44, and 40.70% in the stems, and by 31.20, 26.61, and 32.47% in the leaves, respectively. Furthermore, the I, PI, and increased Mg^{2+} content by 157.89, 174.32, and 167.05% in the roots, by 140.12, 160.78, and 155.83% in the stems, and by 66.20, 70.57, and 74.40% in the leaves, respectively.

Compared with the S, P, and SP treatments, the I treatment increased ($P < 0.05$) to 28.80–65.80% in Ca^{2+} content and 63.23–114.20% in Mg^{2+} content. Compared with P, the PI treatment resulted in a significant increase ($P < 0.05$) of 24.30–48.54% in

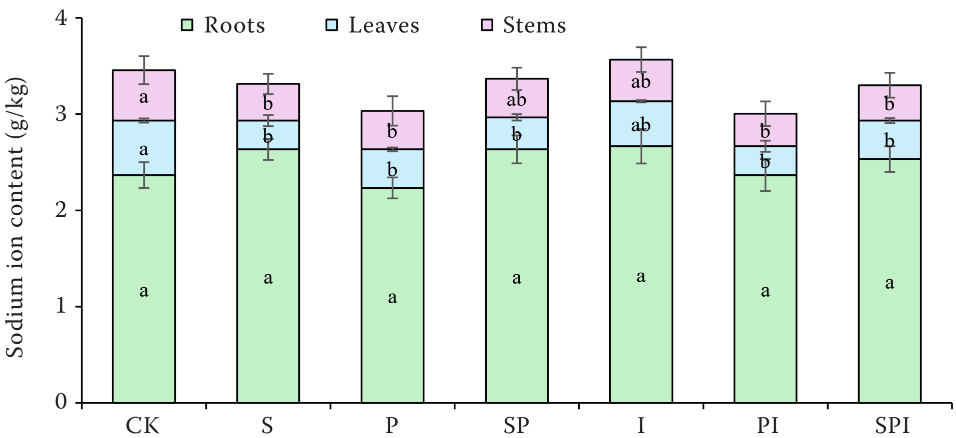

Figure 7. Sodium ion content in various parts of maize plants at maturity. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

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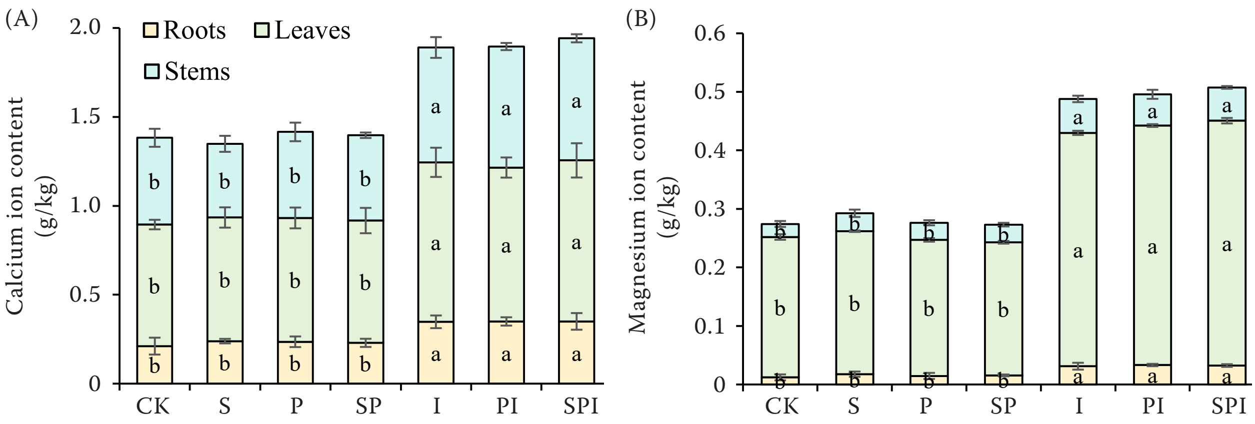

Figure 8. (A) Calcium and (B) magnesium ion contents in various parts of maize plants at maturity. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences (P < 0.05) among treatments

Ca^{2+} and 76.05–127.85% in Mg^{2+} contents. Compared with the SP treatment, SPI resulted in a significant increase (P < 0.05) of 31.66–52.64% in Ca^{2+} and 83.96–108.24% in Mg^{2+} contents.

Plant nutrient contents (N, P, K)

Overall, the general trend for N, P, and K contents in all parts of the maize plant at the maturity stage was as follows: aboveground (stems, leaves, and kernels) > belowground (roots). Some differences were observed in the aboveground and belowground N and P contents among treatments; however, the differences in K content were not significant (Figure 9).

The aboveground N content was significantly higher (P < 0.05) under all treatments except for the S and P treatments, while the belowground N content was significantly higher under all treatments except for the S treatment. Among these, the aboveground N content under the P treatment significantly increased (P < 0.05) by 46.46% compared with that the CK treatment. The N content in each part of the SP treatment significantly increased (P < 0.05) by 18.19% (belowground) and 36.17% (aboveground) compared with that under CK. Under the I treatment, the N content increased significantly (P < 0.05) by 22.43% (belowground) and 38.12% (aboveground), whereas under the PI and SPI treatments, it increased by 34.86% and 19.82% (belowground) and 38.94% and 42.79% (aboveground), respectively, compared with that under CK.

The belowground P content was significantly higher (P < 0.05) under all treatments, except for the S and SP treatments, compared with that under CK. The aboveground P content was significantly higher (P < 0.05) under the P treatment compared with that under CK. The aboveground and belowground P contents under the P treatment significantly increased (P < 0.05) by 20.52% and 21.98%, respectively, compared with those under CK. Meanwhile, the belowground P content under the I treatment significantly increased (P < 0.05) by 25.15% compared with that under CK, while under the PI and SPI treatments, it increased by 32.09% and 27.33%, respectively.

Plant K^+/Na^+, Ca^{2+}/Mg^{2+}

In plants, K^+ is often redistributed from older to younger tissues, Mg^{2+} is an essential component of chlorophyll, and Ca^{2+} is a crucial nutrient that plants can absorb and utilise. Plants require a high nutrient supply for photosynthesis and transpiration; therefore, there is a high demand for K^+, Ca^{2+}, and Mg^{2+}. Na^+ is the primary toxic salt-based ion in plants, and excessive Na^+ can inhibit plant growth. Consequently, a higher K^+/Na^+ ratio is more favourable for plant growth. Similarly, a lower Ca^{2+}/Mg^{2+} ratio indicates a more balanced distribution of Ca^{2+} and Mg^{2+}, which is also beneficial for plant growth.

Significant differences were observed in the K^+/Na^+ and Ca^{2+}/Mg^{2+} ratios among treatments in different parts of the maize plant (Table 1). In leaves, the K^+/Na^+ ratio significantly increased (P < 0.05) by 62.62–123.83% under all treatments compared with that under CK, except for the I treatment. In stems, the K^+/Na^+ ratio significantly increased (P < 0.05) by

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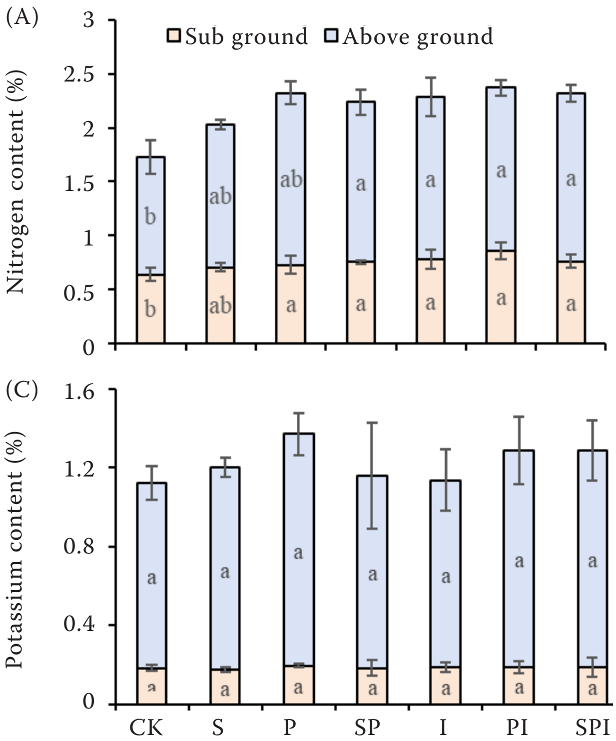

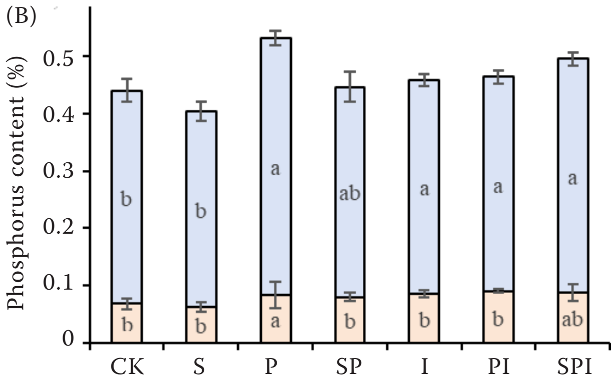

Figure 9. (A) Nitrogen; (B) phosphorus, and (C) potassium accumulation in the dry weight (DW) of various parts of maize plants at maturity. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences (P < 0.05) among treatments

39.14–75.11% under all treatments compared with that under CK.

The Ca^{2+}/Mg^{2+} ratio in each plant part significantly decreased (P < 0.05) under the I, PI, and SPI treatments compared with that under CK. Specifically, the I treatment reduced the Ca^{2+}/Mg^{2+} ratio by 36.09% (roots), 21.08% (leaves), and 49.25% (stems); the PI treatment reduced the ratio by 39.55% (roots), 25.79% (leaves), and 41.93% (stems); and the SPI treatment reduced the ratio by 37.87% (roots), 24.06% (leaves), and 45.01% (stems).

Plant physiological indicators (SOD, POD, MDA, and H_2O_2)

The application of straw return or an inorganic improver increased plant SOD and POD activities (Figure 10A, B), with increase of 11.55–28.80% SOD

Table 1. Ratios of K^+/Na^+ and Ca^{2+}/Mg^{2+} in maize plants under different treatments

Ion ratio	Plant organs	CK	S	P	SP	I	PI	SPI
K^+/Na^+	roots	0.77 ± 0.05^a	0.66 ± 0.02^a	0.88 ± 0.01^a	0.70 ± 0.06^a	0.70 ± 0.12^a	0.80 ± 0.07^a	0.74 ±0.04^a
	stems	5.92 ± 1.14^b	8.24 ± 1.06^a	9.25 ± 0.99^a	9.35 ± 1.03^a	8.65 ± 1.19^a	10.37 ± 1.16^a	10.22 ± 1.21^a
	leaves	11.12 ± 2.03^b	23.81 ± 1.99^a	20.11 ± 3.11^a	18.08 ± 3.41^a	12.33 ± 2.86^b	24.89 ± 3.19^a	18.13 ± 3.12^a
Ca^{2+}/Mg^{2+}	roots	17.42 ± 4.12^a	13.58 ± 3.21^{ab}	16.15 ± 3.33^a	14.76 ± 3.09^{ab}	11.13 ± 3.44^b	10.53 ± 3.28^b	10.82 ± 4.09^b
	stems	21.95 ± 1.96^a	13.53 ± 1.88^b	16.51 ± 2.24^{ab}	15.92 ± 3.12^{ab}	11.14 ± 1.56^b	12.75 ± 3.02^b	12.07 ± 2.63^b
	leaves	2.85 ± 0.96^a	2.85 ± 1.56^a	3.00 ± 1.25^a	3.02 ± 1.33^a	2.25 ± 1.66^b	2.12 ± 1.05^b	2.16 ± 1.28^b

CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences (P < 0.05) among treatments

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and 3.02–8.92% POD relative to that under CK. No significant differences were observed among the S, P, SP, and I treatments or between the PI and SPI treatments. Meanwhile, compared with P, the PI treatment significantly increased ($P < 0.05$) SOD activity by 8.30%, while the SPI treatment significantly increased ($P < 0.05$) SOD activity by 6.46% compared to the SP treatment. The PI and SPI treatments also significantly increased ($P < 0.05$) SOD activity by 14.88% and 15.46%, respectively, compared with the I treatment. Although POD content increased under the PI and SPI treatments compared with that under the single treatment, the difference was not statistically significant.

Plant MDA and H_2O_2 levels decreased following straw return or inorganic improver application (Figure 10C, D), with reduction of 24.77–36.66% MDA and 8.30–12.89% H_2O_2 relative to that under CK. No significant differences were observed among the S, P, SP, and I treatments or between the PI and SPI treatments. The PI treatment significantly reduced ($P < 0.05$) MDA levels by 10.83% compared with the P treatment, while the SPI treatment significantly reduced ($P < 0.05$) MDA by 8.66% compared with the SP treatment. Furthermore, the PI and SPI treatments significantly reduced ($P < 0.05$) MDA levels by 14.31% and 15.75%, respectively, compared to the I treatment. Although H_2O_2 content decreased under the PI and SPI treatments compared with that under the single treatment, the difference was not statistically significant.

Plant root system configuration

Plant root indicators were significantly increased by straw return and inorganic improver application (Figure 11). Compared to CK, the S, P, and SP treatments, respectively, increased the total length by 27.15, 30.65, and 27.77%, projection area by 51.99, 55.77, and 49.53%, area by 47.98, 46.57, and 47.72%, surface area by 52.00, 55.30, and 49.52%, root tip

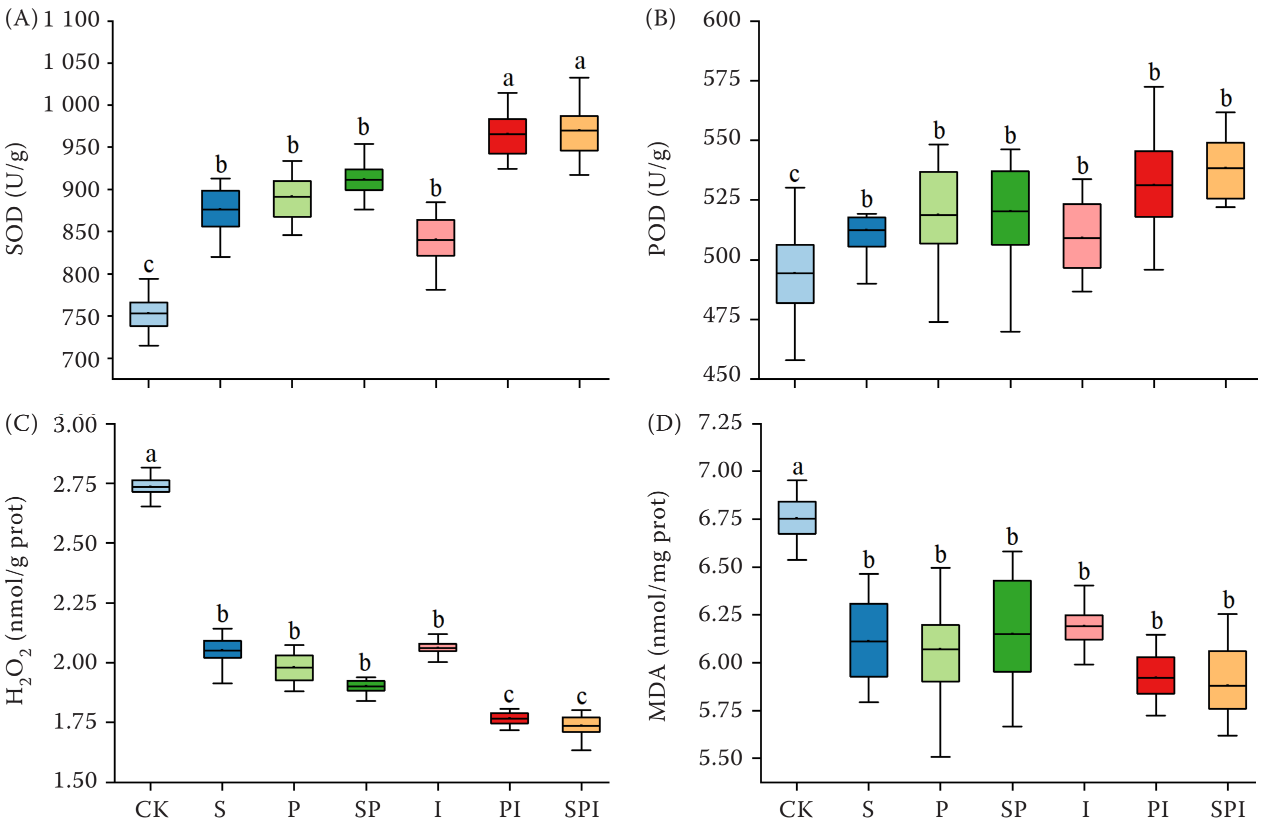

Figure 10. Activities of (A) superoxide dismutase (SOD); (B) peroxidase (POD); (C) malondialdehyde (MDA) and (D) hydrogen peroxide (H_2O_2) levels in plants under different treatments. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

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number by 55.80, 75.37, and 108.05%, and volume by 66.38, 62.10, and 70.73% ($P < 0.05$).

Compared to CK, the PI and SPI treatments, respectively, increased the total length by 47.26% and 56.77%, projection area by 56.17% and 57.34%, area by 81.95% and 67.53%, surface area by 56.17% and 55.77%, root tip number by 98.23% and 146.22%, and volume by 92.93% and 92.00% ($P < 0.05$).

Meanwhile, the PI treatment caused a significant increase ($P < 0.05$) in total length by 12.71%, in area by 24.14%, and in volume by 19.02% compared to the P treatment. The SPI treatment significantly increased ($P < 0.05$) the total length by 22.70%, area by 13.41%, and volume by 12.46% when compared with the SP treatment. Additionally, compared to I, the PI and SPI treatments significantly increased ($P < 0.05$) the total length by 17.82% and 25.42%, area by 44.50% and 33.04%, and volume by 82.00% and 81.13%, respectively.

Principal component analysis

Principal component analysis (PCA) was performed to further examine the differences among various

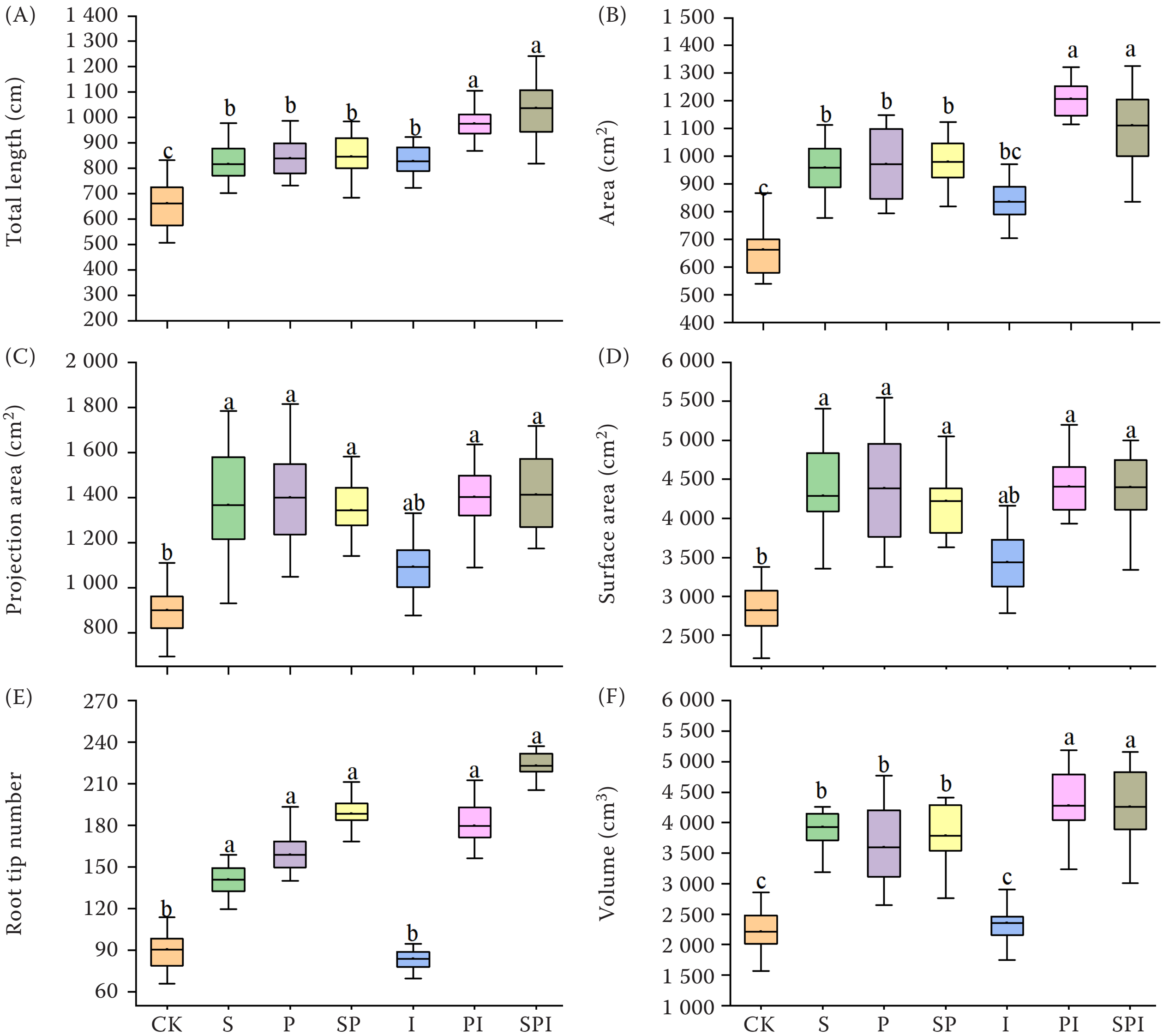

Figure 11. (A) Total root length; (B) root area; (C) projection area; (D) surface area; (E) root tip number, and (F) root volume under different treatments. CK – control; S – straw mulching return; P – straw burial return; SP – straw mulching + straw burial return; I – inorganic improver alone; PI – straw burial return + inorganic improver; SPI – straw mulching + straw burial return + inorganic improver. Mean values with their standard deviations are shown in the figure. Different lowercase letters indicate significant differences ($P < 0.05$) among treatments

treatments and the relationships among the critical indicators (Figure 12).

Among the extracted components, PC1 and PC2 contributed 61.44% and 20.80% of the total variance, respectively, with a combined contribution of 82.24%. Thus, soil salt and nutrient indices were primarily influenced by these two components under the different treatments. The distribution of treatments in the plot indicated that the treatments had distinct effects on soil salt and nutrient indices. PC1, which had the highest contribution, classified the research indicators into two groups. The first group included soil SO_4^{2-}, Mg^{2+}, and Ca^{2+}, all of which were positively correlated with PC1. The second group included soil Na^+, K^+, Cl^-, and HCO_3^-, which were negatively correlated with PC1. PC2, explaining a further 20.80% of the variance, was primarily associated with soil total salt, soil bulk density, and soil organic carbon. Among these, soil bulk density and soil total salt were positively correlated with PC2, whereas soil organic carbon was negatively correlated. Overall, the PI and SPI treatments exhibited similar effects on soil physicochemical properties, which were more pronounced than those of the other treatments.

Among the extracted components, PC1 and PC2 accounted for 83.43% and 4.85% of the total variance, respectively, with a combined contribution of 88.28%. Therefore, plant physiological parameters and root growth were primarily influenced by these two components under the different treatments. The distribution of treatments in the plot revealed that the treatments significantly affected plant physiological parameters and root growth. PC1, which had the highest contribution, classified the research indicators into two groups. The first group included total root length, plant SOD, and root area, all of which were positively correlated with PC1. The second group included plant H_2O_2 and plant MDA, which were negatively correlated with PC1. Overall, the PI and SPI treatments exhibited similar effects on plant physiological parameters and root growth, which were more pronounced than those of the other treatments.

DISCUSSION

Coastal saline soils are characterised by high salinity, poor structure, and other constraints that severely limit crop growth. Salt reduction and soil quality improvement are essential for increasing crop yields in saline soils and are crucial for ensuring national food security and high-quality agricultural development. This study investigated the effectiveness of two different straw return methods and their respective applications of calcium and magnesium mixtures in improving coastal saline-alkaline land. Overall, the effects on soil salt reduction and soil improvement were more pronounced in straw return combined with Ca-Mg application treatment, with substantial

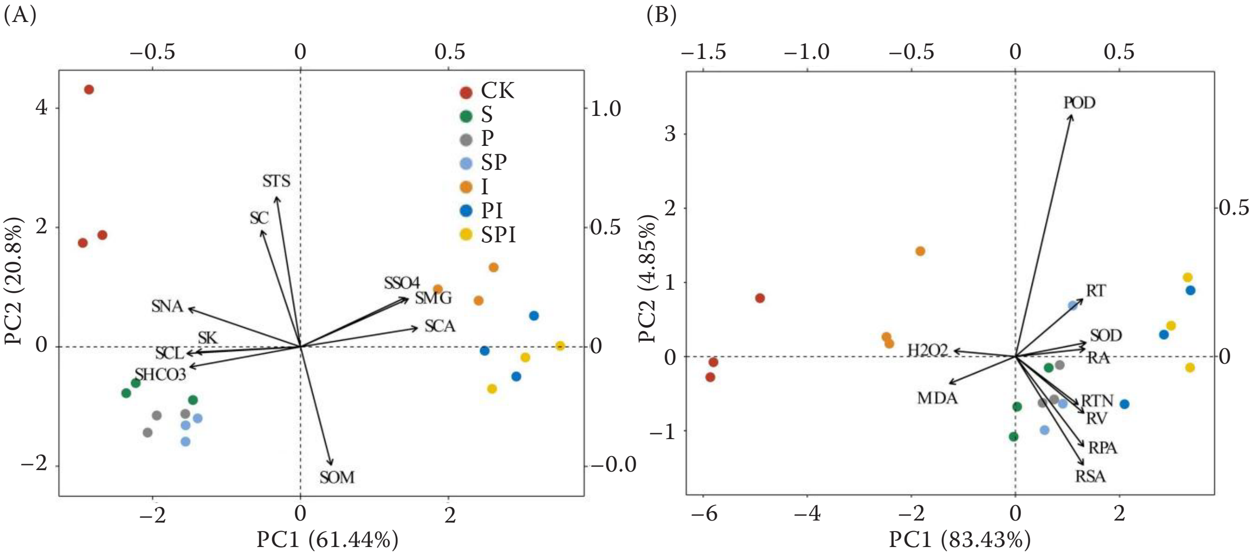

Figure 12. Principal component analysis (PCA) of (A) soil-related and (B) plant-related indices under different treatments. STS – soil total salt; SNA – soil Na^+; SK – soil K^+; SCA – soil Ca^{2+}; SMG – soil Mg^{2+}; SCL – soil Cl^-; SSO4 – soil SO_4^{2-}; SHCO3 – soil HCO_3^-; SOM – soil organic carbon; SC – soil bulk density; SOD – plant SOD; POD – plant POD; MDA – plant MDA; H2O2 – plant H_2O_2; RT – root total length; RPA – root projection area; RA – root area; RSA – root surface area; RTN – root tip number; RV – root volume

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reduction in K^+, Na^+, Cl^-, and HCO_3^- contents as well as a significant reduction in soil bulk density.

The application of straw return or inorganic amendments combined with irrigation drenching effectively enhanced the organic carbon content in the soil, reduced soil bulk density, and promoted crop growth. Furthermore, the S, P, SP, PI, and SPI treatments significantly enhanced the organic carbon content of the tillage soil, aligning with the findings of Zhang et al. (2024b), who reported that straw return effectively increased soil nutrient levels and organic carbon content. Similarly, Li et al. (2024) concluded that straw mulching could effectively enhance the organic carbon content of the soil, increase soil nutrient availability, and improve fertility. Weigand et al. (2024) demonstrated through soil column leaching and field tests that the application of calcium silicate did not substantially improve the organic carbon content of the soil, indicating that the application of a calcium-magnesium mixture alone was insufficient for significantly increasing organic carbon and other soil nutrients. The primary source of nutrients in the soil is the decomposition of straw, and different methods of returning straw to the field provide essential nutrients through straw decay.

Additionally, the present study found that in the tillage soil, soil bulk density was significantly reduced by 7.88–11.82% under the S, P, SP, PI, and SPI treatments. Song et al. (2019) reported that continuous straw incorporation and burial improve soil aeration and permeability and effectively reduce soil bulk density. In this study, the PI and SPI treatments were found to be more effective than the S, P, and SP treatments. Shaaban et al. (2022) concluded that, in addition to salt reduction measures, adding chemical amendments can enhance the reduction of saline soil bulk density and improve soil structure. This suggests that both straw return and inorganic amendments stabilise soil structure, reduce soil bulk density, and fundamentally improve the soil's physical properties. Similarly, Jian et al. (2024) found that the application of chemical amendments alongside straw return effectively reduced soil bulk density, which is consistent with the findings of the present study.

This study demonstrated that the combined treatment of straw return with Ca-Mg application had significant advantages in reducing soil salinity and improving soil structure compared to any single treatment.

Salt stress is the most critical factor inhibiting crop growth. In this study, the content of toxic saline ions in soil was substantially decreased in various straw return methods combined with Ca-Mg application treatments, and the PI and SPI treatments in the tillage soil, were more effective in decreasing salinity than the S, P, SP treatments and I treatment. The Ca^{2+}, Mg^{2+} and SO_4^{2-} contents were higher in the PI and SPI treatments than the other treatments owing to the application of calcium and magnesium mixtures. Most of the toxic saline-ions (Na^+, Cl^-, and HCO_3^-) in the tilled soil were displaced and substantially reduced compared with those in the CK and straw return (S, P, SP) treatments.

This conclusion was further supported by the results of leaching experiments. With the application of inorganic improver (calcium silicate and magnesium sulphate), the Ca^{2+}, Mg^{2+} and SO_4^{2-} contents in the soil from 0 cm to < 40 cm increased. Meanwhile, most of the toxic salts in the tillage soil (Na^+, Cl^-, and HCO_3^-) were displaced and moved downward with the water, owing to which the contents of all salts were significantly reduced compared with those under the straw or inorganic improver treatment alone. The total salt and salt-based ion content in the soil was significantly reduced compared with under the straw alone and inorganic amendment alone treatments; the desalination rate was as high as 60–80% (Wang et al. 2024). Xiong et al. (2024) reached similar conclusions, demonstrating that treatment with an inorganic improver had a greater salt reduction effect than the straw return alone, achieving a substantial reduction of 67.5% in salt content. Chen et al. (2020) found that continuous straw mulching or deep landfilling with chemical amendments for irrigation and drenching significantly decreases the soil tillage's salt content at a desalination rate of 53%, reducing Cl^- and Na^+ by 52.6% and 52.7%, respectively. El-Sharkawy et al. (2024) demonstrated that gypsum-based inorganic materials can utilise Ca^{2+} and other metal ions to displace Na^+ in the soil, achieving a 60.4% salt reduction – surpassing the 36.25% reduction achieved with the straw return treatment. These findings illustrated that, while straw return has a limited effect on soil salinity reduction, chemical amendments provide a more effective solution. Yan et al. (2024) concluded that the salt reduction achieved through straw returned to the field was primarily realised by reducing water evaporation and inhibiting salt return. In contrast, the application of chemical amendments more effectively displaced saline ions, leading to a greater reduction in soil salinity. Through the saline soil's

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salt reduction and improvement, the salt stress that the plant suffered was effectively alleviated, and the soluble salts absorbed from the soil by the plant's root system under each treatment considerably differed.

Furthermore, differences were observed in the distribution and accumulation of soluble K^+, Na^+, Ca^{2+}, and Mg^{2+} within the plant, owing to the distinct roles and transport mechanisms of these individual ions in the maize. The different ways of returning the straw to the field or the matching application of inorganic improvers could all substantially reduce the Na^+ content in maize leaves and stems and had no significant effect on the K^+ content. Therefore, the K^+/Na^+ in maize leaves and stems of all treatments were considerably increased compared to CK, aligning with the conclusion drawn by Liang et al. (2024).

In contrast, Ca^{2+} and Mg^{2+} concentrations in all parts of maize were significantly higher under the PI and SPI treatments, whereas the Ca^{2+}/Mg^{2+} ratio was significantly lower than that under the CK treatment. This indicated that Ca^{2+} and Mg^{2+} levels in maize tended to reach equilibrium, substantially promoting plant growth and development. This is because the ameliorator and Na^+ in the soil exhibit a displacement reaction, prompting the Na^+ downward. The Na^+ content in the soil is substantially reduced, with a reduction in the absorption by maize plants. Meanwhile, the Ca^{2+} and Mg^{2+} from the ameliorator were absorbed in large quantities and accumulated in the plant.

Therefore, straw return combined with a calcium-magnesium mixture can better alleviate soil salt stress than single treatments, consistent with the findings of Yaseen et al. (2022). Additionally, this study proved that different straw return methods, along with calcium and magnesium mixtures, effectively decrease plant MDA and H_2O_2 contents while increasing POD and SOD activities, which aligns with the findings of Xu et al. (2024) and Qi et al. (2023). These authors concluded that straw return, through physiological and biochemical pathways – such as decreasing MDA and H_2O_2 content and enhancing POD and SOD activities – could effectively alleviate salinity's negative effects stress on crops and promote crop growth and development. Zhao et al. (2020) reported that inorganic amendments reduced oxidative stress by increasing plants' antioxidant enzyme activities (SOD and POD), thereby reducing MDA and H_2O_2 accumulation and significantly improving root morphology indices and maize growth. When we combined the two approaches, we achieved significant results compared to the single treatment in other studies. Additionally, Liu et al. (2024) concluded that the application of inorganic amendments improved soil conditions for plant root growth and development, and the root morphology indices (root tips, root length, root surface area, and volume) were substantially improved.

PI and SPI treatments significantly reduced MDA and H_2O_2 content, significantly increased the POD and SOD activities, and improved the root length, surface area, and volume compared to the S, P, and SP treatments. These findings suggest that straw return combined with Ca-Mg is more significant for growth promotion of maize in coastal saline soils in this study compared to other single treatment studies.

Generally, the findings of this study provide new insights into saline soil improvement and contribute to the advancement of comprehensive strategies for the reclamation and utilisation of coastal saline soils. Additionally, this treatment promoted soil fertility, improved maize yields, and increased farmers' returns. However, further field trials are necessary to assess the effects of specific improvement strategies involving different material combinations.

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