

# Combined application of organic amendments improved soil quality and maize yield in coastal saline soil<sup>☆</sup>

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## ABSTRACT

Organic amendments are widely recognized as efficient strategies to enhance soil fertility and crop yield. However, the impacts of combined application of organic amendments on soil quality and crop yield in saline soils remains incompletely understood. Here, a field experiment was conducted to evaluate soil physical index (SPI, e.g., bulk density, mean weight diameter, and  $R_{0.25}$ ), soil chemical index (SCI, e.g., soil organic carbon and nutrient availability), and soil biological index (SBI, e.g., microbial biomass and enzyme activities) their relationships with soil quality index (SQI) and crop yield under manure combination with straw/biochar. Four treatments included: CK (compound fertilizer), OM (compound fertilizer plus manure), OM + ST (compound fertilizer plus manure plus straw) and OM + BC (compound fertilizer plus manure plus biochar). Our results showed that OM + ST and OM + BC treatments notably changed soil properties across different soil layers. In addition, OM + ST and OM + BC treatments increased SPI, SCI, SBI and SQI by 6.3%–15.9% and 4.8%–19.1% relative to OM across different soil layers. OM + BC treatment notably increased maize yield by 35.2% compared to OM treatment. Linear regression analysis showed that SBI and SPI were key factors influencing maize yield. Variation partitioning analysis further revealed that SPI contributed most to SQI variation across soil layers, whereas SBI exerted the strongest influence on maize yield. Manure combined with straw primarily improved crop yield through regulating SCI and SPI, while manure combined with biochar enhanced crop yield mainly through improvement of SPI and SBI. Overall, our findings provide guidance for improving soil quality and designing sustainable agricultural strategies in coastal saline soil.

## 1. Introduction

Soil is a vital resource that provides a range of essential services such as supporting biodiversity and regulating climate change (Yang et al., 2023; Zhou et al., 2024). Over 3% of global soil are affected by soil salinity, with an additional 2 million ha being affected annually (Wang et al., 2025). Additionally, climate change and human activities have intensified soil salinization, which pose a substantial risk to soil quality and agricultural production (Bai et al., 2026). Therefore, it is imperative to develop effective and sustainable saline-alkali soil improvement

measures.

The application of organic amendments has become an increasingly important strategy for the reclamation of coastal saline-alkali soils (Zhang et al., 2022). Among them, manure, crop straw and biochar have been widely used to improve soil structure, enhance nutrient availability, and alleviate salt stress (Ashraf et al., 2023). Manure application could enhance soil quality and crop yield by promoting plant root development, increasing active SOC fraction, and improving soil structure (Bai et al., 2024; Beltrán-Paz et al., 2024). Incorporating straw to soil could improve soil aggregation, increase soil nutrients levels, and

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promote crop growth by providing a better hydrothermal condition in agroecosystems (Irfan et al., 2025). Biochar, a C-rich material, exhibits superior soil structure improvement and nutrients supply enhancement owing to its high specific surface area and adsorption capacity (Xiang et al., 2026). Although individual organic amendment application can improve saline-alkali soils, their effects are often limited to specific soil properties and may not simultaneously regulate the physical, chemical, and biological processes that determine overall soil quality. Therefore, understanding the mechanistic distinctions between manure-biochar versus manure-straw systems in regulating soil physical, chemical, and biological processes is crucial to improve saline-alkali land.

Soil is a complex ecosystem formed by the interaction of organic matter, organisms, and minerals (Khan et al., 2026). The high coupling of soil processes makes it difficult to comprehensively assess its functions using a single attribute (Bongiorno et al., 2019; Zerizghi et al., 2022). Therefore, choosing measurable, representative, and cost-effective indexes to determine changes in soil quality can identify degraded areas, provide trend warnings, and guide agricultural management (Bünemann et al., 2018). Soil quality index (SQI)—a synthetic indicator—integrates soil chemical, physical and biological indexes to access soil functions (Gabhane et al., 2023), has been widely used in soil quality assessments under diverse conditions (Chang et al., 2023; Soria et al., 2025). To further enhance the scientific rigor of assessments, recent studies have proposed refining the SQI into sub-indices for soil physical, chemical, and biological indexes to more accurately reflect soil quality (Liu et al., 2025). Additionally, crop yield remains a crucial indicator as a direct response to soil quality while it is not always integrated into soil quality evaluation. When SQI shows no significant correlation with crop yield, the SQI loses its biological relevance (Li et al., 2024). Therefore, research have begun to focus on the association between SQI and crop yield in recent years, suggesting that high SQI is typically closely related to high output (Li et al., 2019; Zhang et al., 2023).

The Yellow River Delta covers approximately  $5.45 \times 10^5$  ha and is a typical coastal saline-alkali region that urgently need to be ameliorated for more agricultural production (Chen et al., 2021). A field experiment was conducted to investigate the impacts of combined manure and straw/biochar on SPI, SCI, SBI and examined their relationships with SQI and crop yield. Our aims were: 1) to quantify contributions of SPI, SCI, SBI on SQI, 2) to identify the main factors influencing SQI and maize yield in saline-alkali soils, and 3) to elucidate the connections among organic amendments, SPI, SCI, SBI, SQI and crop yield. We hypothesized that compared to manure alone, the combined application of amendments would yield better improvement of SPI, SCI, SBI, as well as SQI, and ultimately promote crop yield. Our study integrates the assessment of soil physical, chemical, and biological indicators to systematically quantify their respective contributions to overall soil quality and crop yield, thereby offering new insights into the mechanisms underlying soil quality and crop production improvement in coastal saline-alkali agroecosystems.

## 2. Materials and methods

### 2.1. Site description and design

The field experiment was conducted in Dongying City, Shandong Province, China (E118°37', N 37°17') (Fig. S1). This region experiences a warm-temperate, semi-moist continental monsoon climate, characterized by an average annual temperature of 13.3 °C. The mean annual evaporation and precipitation are 1885 mm and 537 mm, respectively. The soil is characterized by salinized tidal soil according to the FAO system. The basic properties of the topsoil (0–20 cm) were as follows: soil organic carbon (SOC) 8.67 g kg<sup>-1</sup>, total nitrogen (TN) 0.80 g kg<sup>-1</sup>, available potassium (AK) 204.41 mg kg<sup>-1</sup>, available phosphorus (AP) 7.25 mg kg<sup>-1</sup>, and pH 8.23; and the subsoil (20–40 cm) were as follows: soil organic carbon (SOC) 6.25 g kg<sup>-1</sup>, total nitrogen (TN) 0.86 g kg<sup>-1</sup>,

available potassium (AK) 216.23 mg kg<sup>-1</sup>, available phosphorus (AP) 12.52 mg kg<sup>-1</sup>, and pH 8.27.

The experiment was arranged in a randomized block design with four treatments and three replications: CK (compound fertilizer), OM (compound fertilizer plus manure), OM + ST (compound fertilizer plus manure plus straw) and OM + BC (compound fertilizer plus manure plus biochar). Each plot size was 100m<sup>2</sup>. All organic amendments were applied on an equal carbon input basis of 5250 kg C ha<sup>-1</sup>. The manure was commercial organic material purchased Shandong Yixing Agricultural Technology Co., Ltd. Maize straw was collected from post-harvest residues, air-dried, and cut into pieces of approximately 3–5 cm prior to application. Biochar was produced from crop straw through pyrolysis under oxygen-limited conditions at about 500 °C and obtained from Shandong TaiTan Biotechnology Co., Ltd. The basic properties of the manure, straw, and biochar are summarized in Table S1. Organic amendments were applied evenly over the soil surface and subsequently mixed into the topsoil using agricultural machinery at the beginning of the experiment in 2022. Each plot received fertilization with 210 kg N ha<sup>-1</sup>, 75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 225 kg K<sub>2</sub>O ha<sup>-1</sup>. The maize cultivar 'Denghai 605' was cultivated with the plant density of 67,500 plants ha<sup>-1</sup> and harvested in October for two consecutive growing seasons (2022–2023).

### 2.2. Soil sampling

At maize maturity in 2023, soil samples were collected from 0 to 20 cm and 20–40 cm depths following an “S” sampling method. Each soil sample was thoroughly mixed and then divided into two subsamples. One subsample was air-dried, passed through a 2 mm sieve for determination of soil physicochemical properties (please see Supplementary Text S1); and the other part was stored at 4 °C for analysis of soil biological characteristics.

### 2.3. Analysis of soil organic carbon fractionation

Microbial biomass carbon (MBC) was measured by classical chloroform fumigation-extraction method (Vance et al., 1987). The available organic carbon of chloroform-fumigated and unfumigated soil samples was extracted with 0.5 M K<sub>2</sub>SO<sub>4</sub> solution and analyzed using a TOC Elementar (Germany). The MBC content was calculated by dividing the difference between fumigated C and unfumigated C by a correction factor of 0.45. Dissolved organic carbon (DOC) was analyzed using a TOC analyzer (Liang et al., 1997). DOC was extracted with a soil-to-distilled water of 1:5 at 25 °C for 30 min shaken at approximately 250 r min<sup>-1</sup> and then centrifuged. The supernatant was filtered by a 0.45 μm membrane filter and analyzed for C by TOC Elementar (Germany). Readily oxidizable organic carbon (ROC) was quantified through the potassium permanganate oxidation method, with absorbance measured by a spectrophotometer according to Blair et al. (1995). Briefly, 5 g of air-dried soil were oxidized by 333 mmol KMnO<sub>4</sub> with a soil to extraction ratio of 1:5. The centrifuge tubes were shaken 1 h at 200 r min<sup>-1</sup> and then centrifuged 5 min at 4000 r min<sup>-1</sup>. Following 0.2 mL supernatant diluted with deionized water to 50 mL, and the absorbance at 565 nm was measured spectrophotometer.

### 2.4. Analysis of soil enzyme activities

The activities of β-D-1,4-glucosidase (BG), β-xylosidase (BX), β-D-1,4-cellobiohydrolase (CBH), β-1,4-N-acetylglucosidase (NAG), L-leucine aminopeptidase (LAP) and alkali phosphate (ALP) were measured based on 96 well microplates method (Marx et al., 2001). Briefly, 1 g of fresh soil was suspended in 50 mL of distilled water by shaking for half an hour. After stirring, the soil suspension (200 μL) was added to the black 96 wells microplate and add 50 μL of 100 μM fluorogenic substrate for each target enzyme. Incubate the microplate and mixed solution at 25 °C for 4 h, then stop subsequent reactions by adding

10 μL 1.0 M NaOH. Fluorescence intensity was read using a microplate fluorometer with excitation and emission filters at 355 and 460 nm, respectively.

### 2.5. Soil quality index evaluation

25 soil properties were collected from each experimental plot. The assessment of SQI, SPI, SCI, and SBI involves selecting relevant properties and converting them to a value of 0 to 1 according to Eq. (1) and (2) (Aon et al., 2001; Levi et al., 2020; Serri et al., 2022). Soil properties were assigned to two groups: if each property increased with soil quality, then a score “more is better” was applied (e.g., SOC) in Eq. (1); instead, a score “less is better” was applied (e.g., EC) in Eq. (2). Then SQI, SPI, SCI, and SBI were calculated using Eq. (3) (Kuzyakov et al., 2020).

$$Li = \frac{x}{x_{max}} \tag{1}$$

$$Li = \frac{x_{min}}{x} \tag{2}$$

$$SQI(SPI, SCI, SBI) = 0.5 \times \sum_i^n Li^2 \times \sin\left(\frac{2\pi}{n}\right) \tag{3}$$

where  $L_i$  is soil indexes;  $x$ ,  $x_{max}$ ,  $x_{min}$  are measured, maximum and minimum values of each property, respectively.  $n$  is number of soil properties.

### 2.6. Crop yield measurement

At the maturity stage, the maize yield was determined by harvesting 2 interior rows in each plot with 5 m length, and yield was normalized to 14% grain moisture content.

### 2.7. Statistical analysis

One-way ANOVA and least significant difference (LSD) test ( $P <$

0.05) were used to determine the effect of treatments on soil indicators in SPSS 26.0 (IBM Corporation, Armonk, USA). Variation partitioning analysis (VPA) was implemented to quantify relative contribution of SPI, SCI, and SBI to SQI and maize yield. Linear regression analysis was used to examine the relationships among SPI, SCI, SBI, SQI and maize yield. Random forest (RF) model was performed to identify the primary factors influencing SPI, SCI, and SBI. Mantel test implemented with the “LinKET” package was employed to assess the effects of soil properties on crop yield and SQI. Partial least squares path modeling (PLS-PM) was constructed to quantify effects of organic amendments, SPI, SCI, SBI and SQI on crop yield.

## 3. Results

### 3.1. Effects of organic amendments on soil properties

Manure combined with straw/biochar significantly affected soil physical, chemical, and biological properties across soil layers (Fig. 1, Table S2). Compared with OM treatment, both OM + ST and OM + BC treatments improved MWD and  $R_{0.25}$  in the topsoil and subsoil (Fig. 1a, d). OM + ST treatment also led a notable reduction in soil pH relative to CK treatment in the topsoil and subsoil ( $P < 0.05$ ). In addition, compared to OM treatment, OM + ST and OM + BC treatments significantly elevated SOC, ROC, MBC and TN contents in the topsoil ( $P < 0.05$ , Fig. 1b, c). For soil enzymes activities, compared with OM treatment, OM + ST treatment significantly increased BG and CBH in the topsoil, while OM + BC treatment significantly improved NAG and LAP in the topsoil and NAG, LAP and ALP in the subsoil ( $P < 0.05$ , Fig. 1c, f).

### 3.2. Soil quality evaluation and maize yield

In the topsoil, OM + ST treatment notably increased SPI and SCI values in comparison to OM treatment (Fig. 2a), and OM + BC treatment also increased SPI by 25.6% compared to OM treatment. OM + ST and OM + BC treatments notably elevated SQI by 25.6% and 23.9%

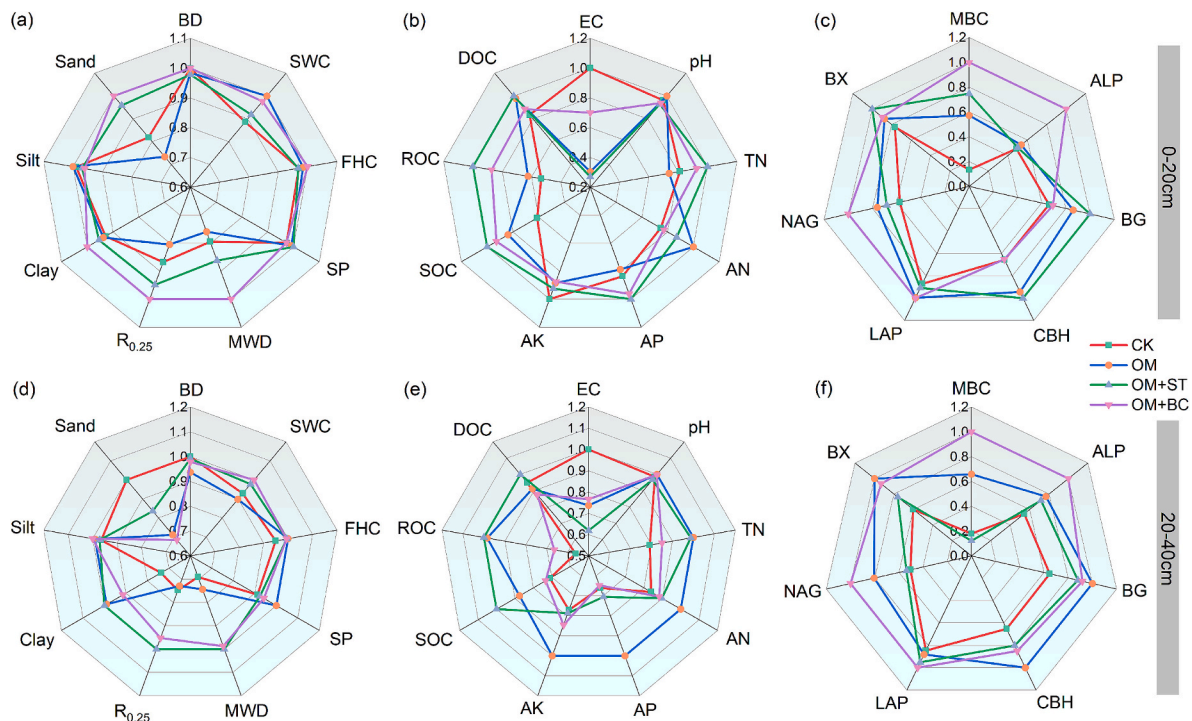
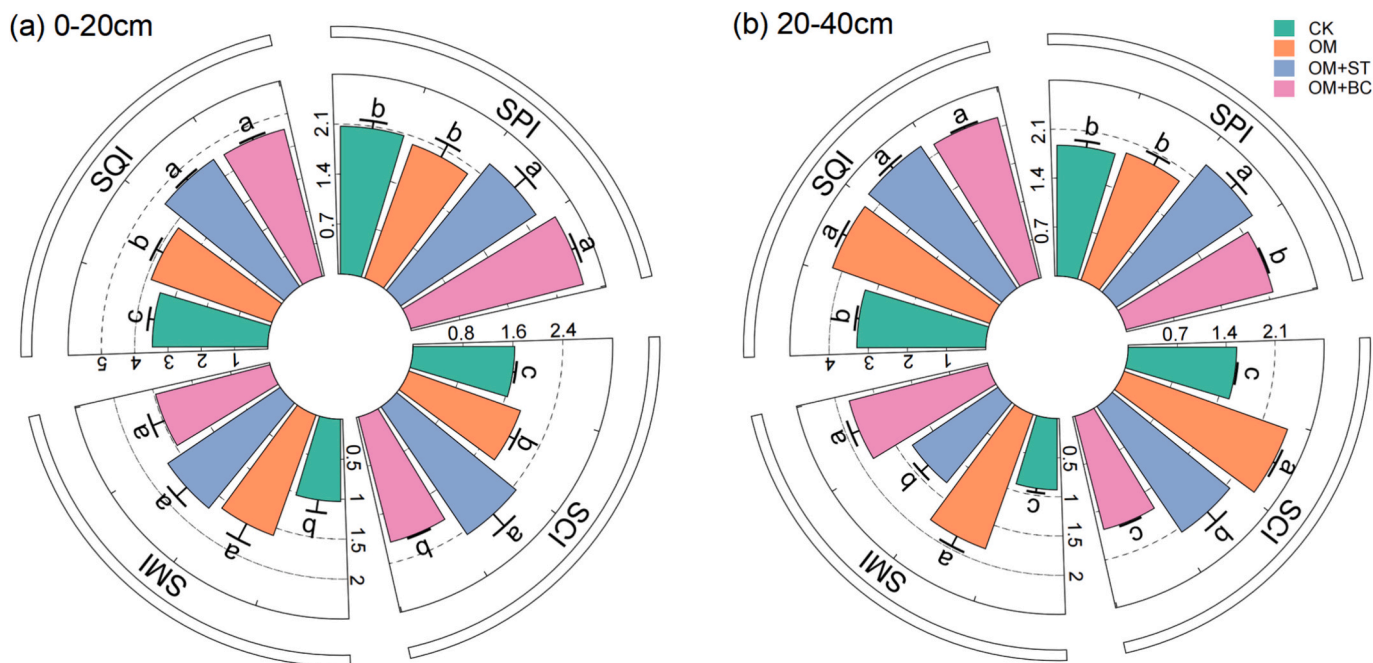


Fig. 1. Radar chart shows the effects of different treatments on soil physical (a, d), chemical (b, e) and biological (c, f) properties at 0–20 cm and 20–40 cm. CK (compound fertilizer), OM (compound fertilizer plus manure), OM + ST (compound fertilizer plus manure plus straw) and OM + BC (compound fertilizer plus manure plus biochar).

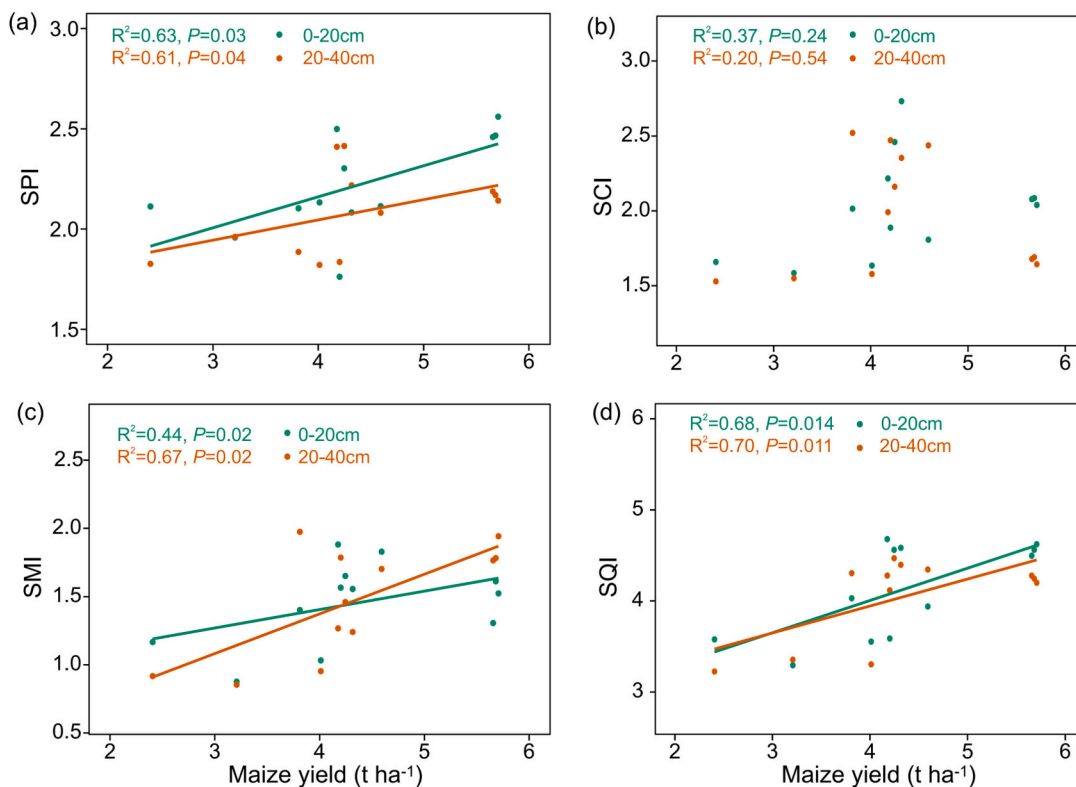


**Fig. 2.** Impacts of different treatments on SPI, SCI, SBI and SQI at 0–20 cm (a) and 20–40 cm (b), respectively. Lowercase letters indicate a significant difference between different treatments in the same soil layer. SPI, soil physical index; SCI, soil chemical index; SBI, soil biological index; SQI, soil quality index. CK (compound fertilizer), OM (compound fertilizer plus manure), OM + ST (compound fertilizer plus manure plus straw) and OM + BC (compound fertilizer plus manure plus biochar).

compared to OM treatment ( $P < 0.05$ ). In the subsoil, OM + ST treatment notably increased SPI by 26.4% compared to OM treatment (Fig. 2b,  $P < 0.05$ ). In addition, OM + BC treatment notably increased crop yield by 35.2% compared to OM treatment (Fig. S2).

### 3.3. Association between soil quality and maize yield

Linear regression analysis showed that SBI, SPI and SQI notably impacts maize yield (Fig. 3;  $P < 0.05$ ). Random forest analysis revealed



**Fig. 3.** Relationship between maize yield and SPI (a), SCI (b), SBI (c) and SQI (d) at depths of 0–20 cm and 20–40 cm, respectively. SPI, soil physical index; SCI, soil chemical index; SBI, soil biological index; SQI, soil quality index.

that MWD,  $R_{0.25}$  and FHC were powerful variables to predict SPI in combination with BD and SP (Fig. 4a, d). In addition, soil texture (silt+clay) played a vital role in predicting variations of SPI in the topsoil and subsoil. SCI were mainly explained by SOC, ROC, pH, TN and DOC in the topsoil, while TN, AP, ROC, SOC and AN had a more pronounced impact in the subsoil (Fig. 4b, e). Moreover, CBH, NAG, and MBC were important factors affecting SBI across different soil layers (Fig. 4c, f). VPA results revealed that variation in SQI was mainly affected by SPI, which explained 32% and 38% of the variation in the topsoil and subsoil, respectively (Fig. 5a, c). Variations in maize yield were largely explained by SPI in the topsoil (Fig. 5b), and SBI had a more evident effect on maize yield in the subsoil (Fig. 5d).

Mantel test analysis revealed that crop yield and SQI were significantly associated with MWD, AK, SOC, and MBC in the topsoil ( $P < 0.05$ , Fig. 6a). And crop yield and SQI were significantly correlated with MWD, sand, EC, ALP, BG and BX in the subsoil (Fig. 6b). Partial least squares path modeling (PLS-PM) revealed that OM + ST and OM + BC treatments positively affected SCI and SBI in the topsoil, this effect exerted a positive influence on SQI, ultimately contributing to higher yields (Fig. 7a). In the subsoil, OM + ST treatment had direct positive effects on SCI and SPI, which positively affected SQI and increased crop yield, while OM + BC treatment positively influenced SPI and SBI, which exhibited direct positive effect on SQI and increased crop yield (Fig. 7b).

#### 4. Discussion

##### 4.1. Soil properties under organic amendments

Soil physical properties such as soil bulk density, soil porosity, and soil aggregates can have a significant impact on soil nutrients cycling and C dynamics by affecting the availability of oxygen, water, and nutrients to soil microorganisms (Chen et al., 2023). OM + ST treatment had a significant influence on SPI in both topsoil and subsoil compared to CK and OM treatments, with reducing soil bulk density, improving

soil structure, increasing soil porosity and field hold capacity (Fig. 1a, d; Table S2), consistent with previous studies (Mi et al., 2021; Lin et al., 2024). These results may be due to straw incorporation introduces labile organic C and essential nutrients, which promoted formation of soil aggregates (Al-Elwany et al., 2023). Straw releases organic substances such as polysaccharides and organic acids, and the humus produced by enhanced soil microbial activity aggregates straw residues and minerals into large aggregates, ultimately improving soil structure (Feng et al., 2026). In addition, straw incorporation can improve soil pore distribution and aeration conditions, which may stimulate microbial activity and accelerate straw decomposition to generate new biopores via fungal hyphae (Ding et al., 2024).

The reduction in soil electrical conductivity (EC) and pH following the incorporation of straw and manure can be attributed follows: The organic acids produced during organic matter decomposition, which react with alkaline substances in the soil (Sun et al., 2025). Concurrently, the decomposition of straw-derived organic carbon—generally considered labile carbon, enhances the microbial utilization of polymers (Ndzelu et al., 2020), which in turn act as salt adsorbents, reducing the concentrations of  $Na^+$  and  $Cl^-$  in saline-alkali soils (Xuan et al., 2022). OM + ST and OM + BC treatments also catalyzed substantial nutrient enhancement (Fig. 1b, e). This involves direct inputs: the application of organic materials introduces labile carbon substrates and nutrients (Akhtar et al., 2018; Chang et al., 2023). Reduced soil bulk density and increased porosity created more favorable conditions for crop growth (Zhou et al., 2022), promoting deeper root development and greater root exudation, which enhanced SOC accumulation and available nutrient pool after maize harvest (Song et al., 2024). Moreover, improved soil structure increased water infiltration and leaching efficiency, thereby reducing salinity, alleviating osmotic stress, and facilitating microbial proliferation and nutrient accumulation (Xuan et al., 2022). OM + BC treatment led to a higher DOC and ROC content, this result may be due to the combined application of manure and biochar notably promoted maize production (Fig. S2) to provide more roots, residues, and root

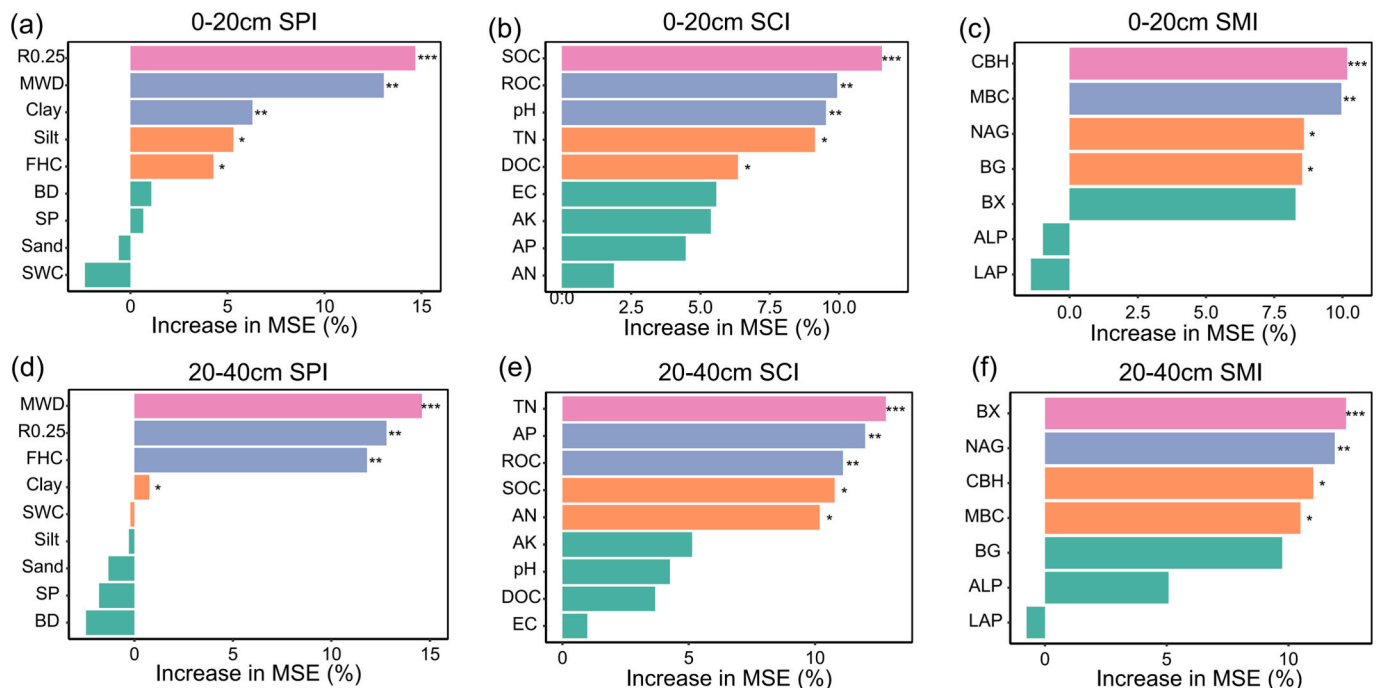
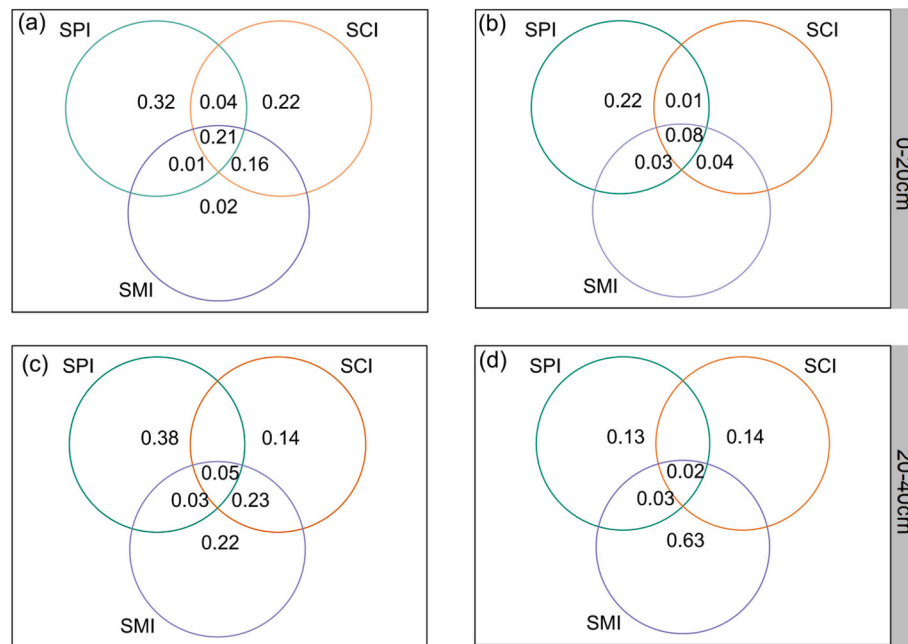
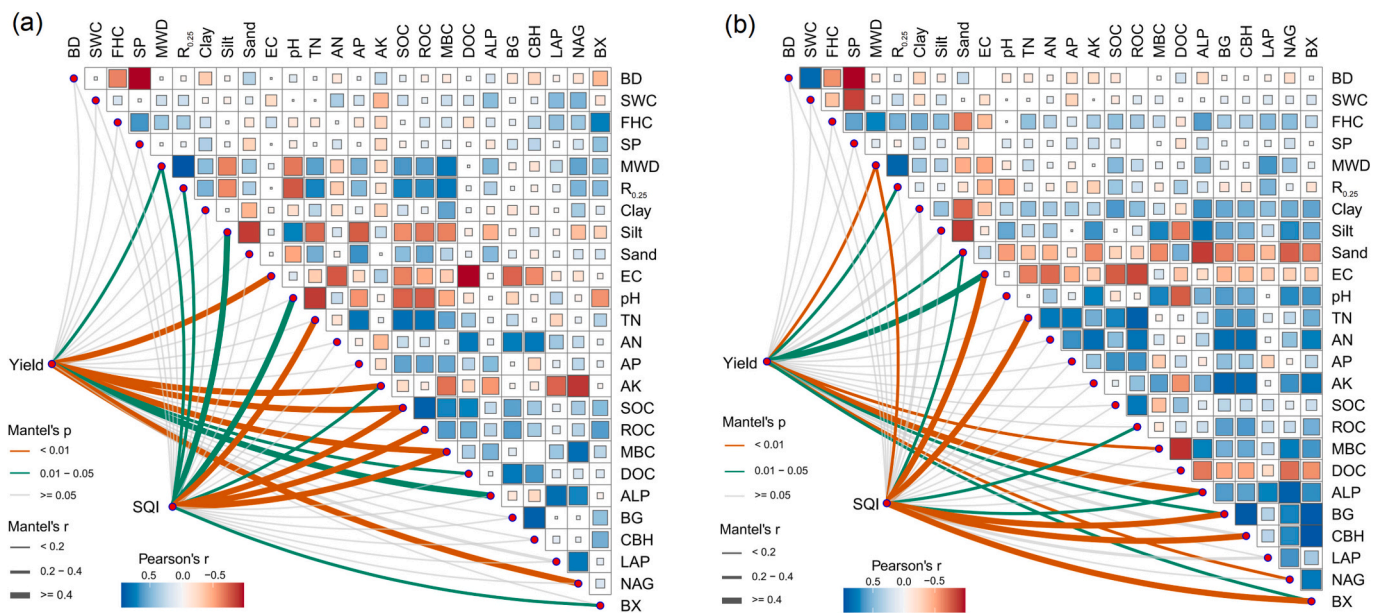


Fig. 4. Random forest analysis of the importance of factors affecting SPI (a, d), SCI (b, e) and SBI (c, f) at depths of 0–20 cm and 20–40 cm, respectively. BD, bulk density; SWC, soil water content; FHC, field hold capacity; SP, total porosity; MWD, mean weight diameter; EC, electrical conductivity; TN, total nitrogen; AN, available nitrogen; AP, available phosphorus; AK, available potassium; SOC, soil organic carbon; ROC, readily oxidizable organic carbon; DOC, dissolved organic carbon; MBC, microbial biomass carbon; BG,  $\beta$ -1, 4-glucosidase; BX,  $\beta$ -xylosidase; CBH,  $\beta$ -cellobiohydrolase; NAG,  $\beta$ -1,4-Nacetylglucosaminidase; LAP, L-leucine aminopeptidase; ALP, alkali phosphatase. SPI, soil physical index; SCI, soil chemical index; SBI, soil biological index; SQI, soil quality index.



**Fig. 5.** Variation partitioning analyses (VPA) showed the relative contributions of SPI, SCI, and SBI to SQI and yield at 0–20 cm (a, c) and 20–40 cm (b, d). SPI include BD, bulk density; SWC, soil water content; FHC, field hold capacity; SP, total porosity; MWD, mean weight diameter;  $R_{0.25}$ ; Clay; Silt; Sand. SCI including EC, electrical conductivity; pH; TN, total nitrogen; AN, available nitrogen; AP, available phosphorous; AK, available potassium; SOC, soil organic carbon; ROC, readily oxidizable organic carbon; DOC, dissolved organic carbon; SBI including MBC, microbial biomass carbon; BG,  $\beta$ -1, 4-glucosidase; BX,  $\beta$ -xylosidase; CBH,  $\beta$ -cellulohydrolase; NAG,  $\beta$ -1,4-Nacetylglucosaminidase; LAP, L-leucine aminopeptidase; ALP, alkali phosphatase. SPI, soil physical index; SCI, soil chemical index; SBI, soil biological index; SQI, soil quality index.

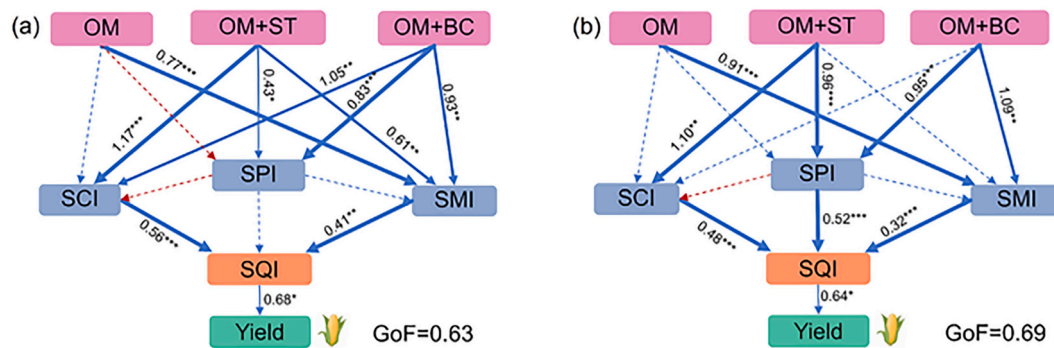


**Fig. 6.** Mantel test analysis between crop yield, SQI and soil indicators in the 0–20 cm (a) and 20–40 cm (b) soil layers. BD, bulk density; SWC, soil water content; FHC, field hold capacity; SP, total porosity; MWD, mean weight diameter; EC, electrical conductivity; pH; TN, total nitrogen; AN, available nitrogen; AP, available phosphorous; AK, available potassium; SOC, soil organic carbon; ROC, readily oxidizable organic carbon; DOC, dissolved organic carbon; MBC, microbial biomass carbon; BG,  $\beta$ -1, 4-glucosidase; BX,  $\beta$ -xylosidase; CBH,  $\beta$ -cellulohydrolase; NAG,  $\beta$ -1,4-Nacetylglucosaminidase; LAP, L-leucine aminopeptidase; ALP, alkali phosphatase.

exudates (an important source of DOC and ROC) to the soil, consequently enhancing the concentrations of DOC and ROC (Xu et al., 2025).

Our findings indicated that manure combined with straw/biochar elevated soil enzyme activities (Fig. 1c, f). This was expected, as organic amendments increased SOC and nutrient availability as mentioned above, these nutrients elevation may stimulate microbial growth, and

accelerate the secretion of soil enzymes (Pokharel et al., 2020; Zhou et al., 2022). Additionally, organic amendments promotes crop growth and rhizosphere C accumulation, ultimately stimulating microorganisms to produce more soil enzymes (Zang et al., 2017). Concurrently, improved soil physical conditions under OM + ST and OM + BC enhanced soil water retention and aeration, which could provide



**Fig. 7.** Partial least squares path modeling (PLS-PM) showing the influence of organic amendments, SPI, SCI, and SBI on SQI and yield at 0–20 cm (a, c), 20–40 cm (b, d), respectively. Blue and red lines indicate positive and negative relationships, respectively. The arrow width is proportional to the correlation strength. Path coefficients are represented by adjacent numbers labeled in the same direction as the arrow. Dashed lines indicate no significant effect. Significant levels are denoted as \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ , respectively. OM (compound fertilizer plus manure), OM + ST (compound fertilizer plus manure plus straw) and OM + BC (compound fertilizer plus manure plus biochar). SQI, soil quality index; SPI, soil physical index; SCI, soil chemical index; SBI, soil biological index.

favorable conditions for microbial activity and stimulate the synthesis and secretion of various enzymes (Wang et al., 2026). The observed enhancement in MBC under amendment treatments is potentially linked to improvement of soil structure, which increases soil aeration and boosted the activity of soil microorganism (Liu et al., 2022). Furthermore, improved soil structure could facilitate root development and enhance the input of root-derived carbon into the soil (Yang et al., 2020).

#### 4.2. Soil quality under organic amendments

As anticipated, OM + ST and OM + BC treatments notably improved soil quality compared to OM and CK treatments, which was identical to the previous studies (Bhogal et al., 2018; Liu et al., 2023). This improvement could be partially attributed to the improved availability of macronutrients released from organic amendments (Das et al., 2025). Organic amendments supplied more substrates for microbial growth, stimulating C, N, and P acquiring enzyme activities and increasing labile C components, ultimately improving soil quality (Song et al., 2023). Moreover, increased soil porosity under organic amendment treatments further supported microbial enzyme production, promoting soil C and N cycling and increasing nutrient status, which collectively elevated SQI (Feng et al., 2024). Reduced salinity further improved SQI by promoting soil enzyme activity and nutrient supply (Li et al., 2023).

#### 4.3. Yield improvement under organic amendments

Our results depicted that co-application of amendments significantly increased maize yield, this result is likely mediated through multiple mechanisms mediated under the combined treatment: First, co-application of amendments alleviated the detrimental effects of salinity, enhanced water retention, and improved nutrient transformation (Poirier et al., 2018); additionally, the improved soil structure fostered root development, thereby enhancing the capacity of roots to access nutrients and water essential for crop growth (Azim et al., 2024; Nguyen et al., 2024). In addition, a better performance on crop yield under OM + BC than OM + ST is likely due to biochar's ability to improve soil physicochemical properties, especially through its exceptional adsorption capacity, which effectively reduces nutrient leaching while simultaneously raising available nutrient content, thereby promoting crop growth (Meng et al., 2025). Mantel test analysis revealed significant positive correlations between maize yield and MWD, AK, SOC, MBC, ALP, BG and BX (Fig. 6). These results further indicated that soil nutrients, enzymes activities, and soil structure parameters directly influenced yield enhancement. Partial Least Squares Path Modeling (PLS-PM) further confirmed that combined application of amendments

improved crop yield by simultaneously influencing physical, chemical, and biological properties, aligns with previous research showing that amendments application improved soil physical conditions and nutrient status, subsequently affecting agricultural productivity (Mitran et al., 2021; Rodríguez-Berbel et al., 2025).

#### 4.4. Why SPI and SBI are important drivers of high SQI and maize yield?

Soil physical index are crucial for crop production by influencing root growth, improving soil aeration, and promoting nutrient cycling (Yang et al., 2024). In the present study, SPI emerged as the primary driver of soil quality, accounting for 32% and 38% of the variation in soil quality across different soil layers (Fig. 3). In coastal saline soils, poor aggregation, high bulk density, and limited pore connectivity often restrict water infiltration, aeration, and root penetration (Sun et al., 2024). Practices such as organic amendments application can effectively improve soil nutrients and structure, thereby facilitating root elongation and development (Rabot et al., 2018). These improvements alleviated physical constraints on root growth and enhanced the capacity of crops to access water and nutrients in the soil profile. Interestingly, soil biological properties (SBI) had a stronger influence on maize yield in the subsoil layer (20–40 cm) may be attributed to improvements in subsoil structure and microbial activity, which promote root proliferation and deep soil moisture uptake (Bauke et al., 2024). These changes, in turn, stimulate rhizosphere processes by enhancing root exudation and accelerating microbial-mediated nutrient cycling (Zhao et al., 2026). Concurrently, an active rhizosphere characterized by high microbial and enzymatic activities enhances the efficiency of subsoil resource acquisition by increasing nutrient mobilization and mass flow from the surrounding soil matrix (Bhattacharyya et al., 2021). This sustains nutrient availability and water supply throughout the soil profile, ultimately supporting higher crop productivity.

Despite the valuable insights gained from this study, some limitations should be acknowledged. For instance, treatments with straw alone or biochar alone were not included in the experimental design and soil samples during growing seasons were not gathered and measured. Therefore, future studies should incorporate single-amendment treatments (e.g., straw-only and biochar-only) to better disentangle the individual and interactive effects of different organic amendments on soil physical, chemical, biological processes, soil quality and crop production in saline-alkali soils over time. Overall, based on the results of this study, the application of organic amendments in coastal saline-alkali soils should prioritize combined strategies rather than single inputs. It is recommended co-application of manure with straw or biochar to simultaneously improve soil physical structure, nutrient availability, and biological activity, thereby maximizing improvements in soil

quality and crop productivity. In addition, practices such as combining amendments with appropriate tillage are recommended to overcome subsoil limitations (e.g., lower biological activity and poor structure).

## 5. Conclusion

Our findings demonstrated that organic manure combined with straw/biochar increased soil physical, chemical, biological indexes, soil quality and crop yield relative to manure alone. PLS-PM analysis revealed that manure combined with straw primarily improved crop yield by affecting soil physical and chemical indexes, while manure integration with biochar enhanced crop yield mainly through improvement of soil physical and biological indexes. Overall, the synergistic physical, chemical, and biological improvements induced by combined application of organic amendments—enhanced soil structure, reduced soil salinity, nutrient availability, and increased enzyme activity, which collectively support a notable improvement in maize yield.

## CRediT authorship contribution statement

**Xiaolong Bai:** Writing – original draft, Software, Data curation. **Ruixiao Dong:** Software, Investigation, Formal analysis. **Shang Wang:** Writing – review & editing. **Mengmeng Chen:** Investigation. **Xiaobin Li:** Writing – review & editing. **Jing Wang:** Writing – review & editing. **Jie Zhou:** Writing – review & editing. **Yuqi Li:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Hongyuan Zhang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Gilles Colinet:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apsoil.2026.107026>.

## Data availability

Data will be made available on request.

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