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Differential effects of *Phragmites australis* versus *Spartina alterniflora* biochar on salt marsh soil improvement and carbon stabilization

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Biochar is an effective strategy for improving physicochemical properties of coastal salt marsh soil and enhancing carbon stabilization. In this study, *Spartina alterniflora* (*S. alterniflora*) and *Phragmites australis* (*P. australis*) were used as biochar materials. Four pyrolysis temperatures (350 °C, 450 °C, 550 °C, and 650 °C) and three addition amounts (1%, 2%, and 3%) were applied to explore the effects of the two biochars on the physicochemical properties and carbon components of salt marsh soil. The results showed that both *S. alterniflora* biochar (SBC) and *P. australis* biochar (PBC) significantly increased soil pH, cation exchange capacity, and nutrients (SBC: 5.3%–188.6%; PBC: 1.4%–200.9%). The addition of biochar at 3% significantly increased soil total nitrogen (TN), Nitrate nitrogen (NO₃⁻), and available phosphorus (AP) contents, thereby effectively enhancing soil nutrient supply capacity. The addition of SBC and PBC altered the composition of soil organic carbon (SOC), significantly increasing the proportion of mineral-associated organic carbon and thereby promoting SOC stability, particularly under high addition amounts and pyrolysis temperatures. These findings suggest that both SBC and PBC hold promise for improving soil carbon stabilization in coastal salt marsh soils. This study provides a valuable approach for saline–alkali soil remediation in coastal wetlands and offers a potential pathway for the resource utilization of *S. alterniflora* and *P. australis*.

KEYWORDS

biochar, *Phragmites australis*, salt marsh, soil carbon stabilization, *Spartina alterniflora*

1 Introduction

Salt marshes, located in the land–sea intertidal zone, represent the most important type of coastal wetland in China. They serve as a critical bridge linking material cycles and energy flows between terrestrial and marine ecosystems. Due to their high carbon sink potential in the global blue carbon system, these ecosystems play an important role in climate change mitigation (Macreadie et al., 2021; Wang et al., 2025). They also protect coastlines and maintain biodiversity (Möller et al., 2014; Sun L. et al., 2023). However, global climate change and human activities threaten these ecosystems by causing salinization and carbon

loss (Gu et al., 2018). Therefore, effective measures are urgently needed to restore their ecological functions and carbon sink capacity.

Biochar is a carbon-rich solid material produced through the pyrolysis of biomass under oxygen-limited conditions. It is widely applied to improve coastal wetland soil as it can improve the physicochemical properties of saline-alkali soil by increasing soil organic matter (SOM) content, cation exchange capacity (CEC), and microbial activity (Cui et al., 2022; Tang et al., 2025). Although biochar itself may contain soluble salts in some cases (He et al., 2020; Thomas et al., 2013), it still holds potential for saline-alkali soil remediation. However, some studies have reported that its effectiveness can be limited by the leaching of alkali metal ions and carbonates (Li F. et al., 2019; Luo et al., 2016; Liu et al., 2021). Despite reducing soil pH and increasing CEC, biochar addition has not yielded significant improvements in saline-alkali soils (Zhang et al., 2021; Lin et al., 2015; El-Naggar et al., 2019). This inconsistency underscores that the effectiveness of biochar is affected by both soil type and biochar properties (Saifullah et al., 2018). Studies have indicated that under different flooding conditions, the addition of *S. alterniflora* biochar (SBC) significantly affect the physicochemical properties of degraded coastal wetland soils (Yang et al., 2025).

The annual carbon burial amount of blue carbon ecosystems in China is 0.349–0.835 Tg, with salt marshes accounting for approximately 80%. The carbon sink capacity of salt marshes exceeds that of mangroves and seagrass beds (Prakhin et al., 2024; Wang et al., 2025). In salt marshes, approximately 95% of organic carbon is stored in the soil (Alongi, 2020), forming a large and stable carbon pool. However, this stable soil carbon pool is vulnerable to degradation from vegetation loss and human activities. Biochar derived from plant straw can improve coastal salt marsh soil by enhancing the soil carbon pool (Huang and Xiao, 2024), promoting halophyte growth (Cai et al., 2021), and supporting vegetation carbon stabilization (Chen et al., 2022). Biochar input also changes the chemical composition and mineral-binding capacity of soil organic carbon (SOC), thereby regulating the distribution and stability of different carbon fractions. Thus, the response of mineral-associated organic carbon (MAOC) and particulate organic carbon (POC) to biochar addition is particularly critical. Biochar addition can increase soil MAOC levels and improve SOC stability (Chen et al., 2024).

S. alterniflora is a typical invasive species in coastal tidal flats worldwide. Since its introduction, it has expanded across China's coastal regions, changing the structure and function of coastal wetland ecosystems (Okoye et al., 2020; Luo et al., 2026). China has launched a national action plan for the prevention and control of *S. alterniflora* and has carried out large-scale control projects since 2019. However, its high biomass, lignin content, rigid texture, and slow decomposition rate make its straw challenging to dispose of and utilize effectively. Thus, the resource utilization of *S. alterniflora* straw remains an urgent challenge. Therefore, we take the invasive plant *S. alterniflora* and the native plant *P. australis* as the biochar material. Through incubation experiments, we examined how the biochar material, pyrolysis temperature, and addition amount affect soil properties and

carbon stabilization in salt marshes. This study aims to provide a scientific basis for improving salt marsh soil carbon storage in coastal wetlands and for utilizing wetland plants in coastal ecosystems.

2 Materials and methods

2.1 Study area

Yancheng coastal wetland (32°34'–34°28'N; 119°48'–120°56'E) is one of the most extensive coastal wetlands in China (Figure 1). It retains a relatively intact native ecosystem. It is located in the transition zone between the subtropical and warm temperate zones and is characterized by a typical monsoon climate zone. Annual average temperature ranges from 13.7 °C to 14.6 °C, with precipitation averaging 980–1,070 mm. The annual sunshine hours total 2,241–2,390 h, and the frost-free period lasts approximately 209 days. Influenced by tidal dynamics, the soils exhibit obvious salinization (pH = 7.6, EC = 1.5 mS/cm) and pronounced water-salt dynamics. The soil texture is predominantly silty.

S. alterniflora and *P. australis* are the dominant plant communities in this region. *S. alterniflora* exhibits high tolerance to salinity, alkalinity, submergence, and wind. Since its introduction, it has spread rapidly, expanding from the mid- to high-tidal zones and shifting from scattered patches to large continuous stands, thereby becoming the dominant species in the coastal wetland. Meanwhile, native *P. australis* also plays a key role in regulating regional ecological functions and improving soil structure and properties.

2.2 Experimental design

Soil samples were collected from the 0–20-cm layer of the coastal mudflat using a soil drill. Roots and plant debris (>2 mm) were removed after transportation to the laboratory. The soil was then sieved through a 2-mm mesh for homogenization and air-dried under ventilated conditions. The air-dried soil was pre-incubated at 25 °C with moisture maintained at 60% of the maximum water-holding capacity. During the 14-day pre-incubation period, the soil was weighed every 2 days and adjusted to the target moisture content.

The aboveground parts of mature *S. alterniflora* and *P. australis* were collected, washed, and dried in an oven at 60 °C to constant weight. The dried material was ground into powder, sieved through a 100-mesh sieve (0.149 mm), and placed in a crucible. After being compacted and tightly wrapped in tin foil to limit oxygen, the samples were pyrolyzed in a muffle furnace at 350 °C, 450 °C, 550 °C, and 650 °C for 1 h.

SBC and *P. australis* biochar (PBC) prepared at different pyrolysis temperatures (350, 450, 550, and 650 °C) was added according to the ratio of biochar to soil (w: w) of 1%, 2%, and 3%, and biochar was fully mixed with soil. Each treatment included five replicates, resulting in a total of 125 samples. During the 120-day incubation period, the samples were weighed every 1–2 days to replenish water lost by evaporation and ensure the stability of the soil moisture content.

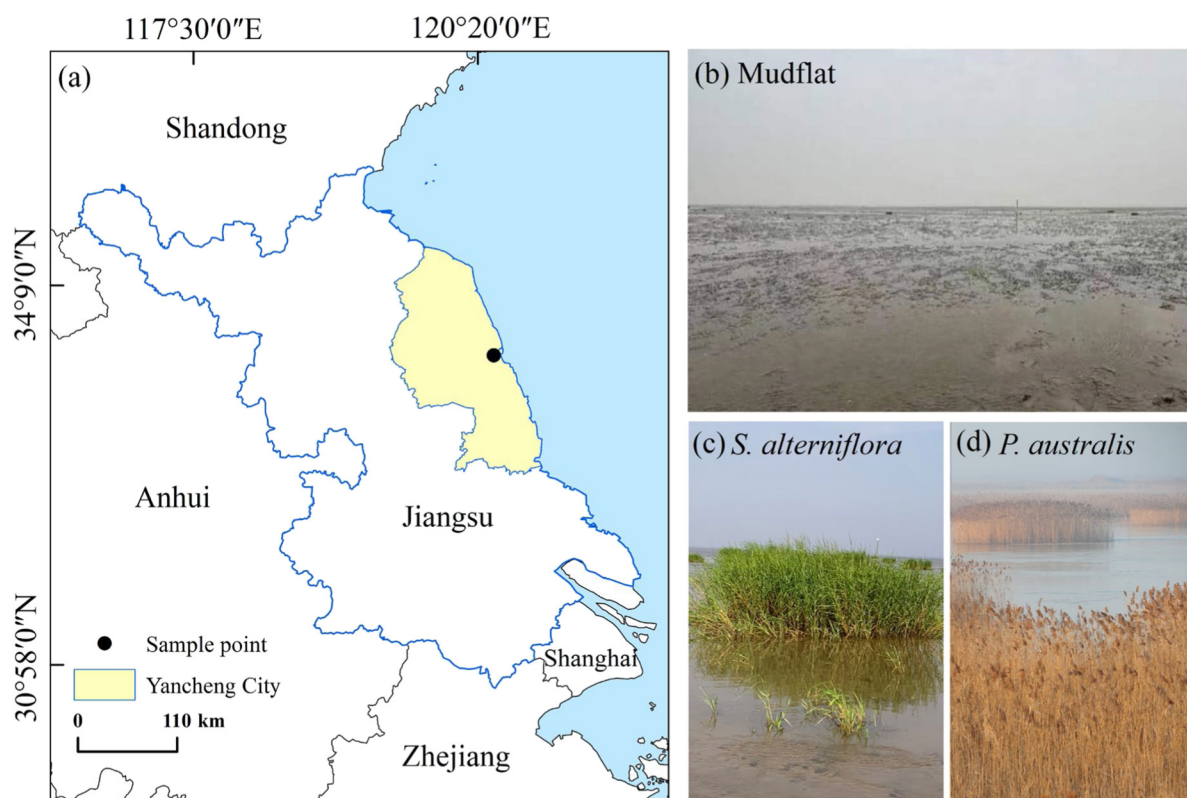


FIGURE 1
Study area. (a) Geographic location of the Yancheng coastal wetlands. (b) Extensive unvegetated mudflats distributed along the coastal area. (c) *Spartina alterniflora* and (d) *Phragmites australis* are the dominant vegetation types in this region.

2.3 Indicator determination

2.3.1 Soil physicochemical indicators

At the end of the experiment, soil pH was measured using a pH meter. Total nitrogen (TN) was determined using a Thermo Scientific elemental analyzer. Nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen were both extracted with $2 \text{ mol} \cdot \text{L}^{-1}$ KCl; the NO_3^- level was measured using dual-wavelength ultraviolet spectrophotometry, while the NH_4^+ level was determined using the indophenol blue colorimetric method. Total phosphorus (TP) was determined after acid digestion using the molybdenum blue method. Available phosphorus (AP) was extracted with sodium bicarbonate and quantified using the molybdenum blue method.

2.3.2 Soil carbon components

2.3.2.1 SOC fractions

SOC fractions were separated using a combined wet-sieving and particle-size method to isolate POC (particle size $0.053\text{--}2 \text{ mm}$) and MAOC (particle size $<0.053 \text{ mm}$). The samples were ground and passed through a 100-mesh sieve, and their carbon content was determined using an elemental analyzer. The POC content was calculated as follows:

$$\text{POC} = \text{POC}_{\text{particle}} \times f_{\text{mass}}$$

$$\text{POC}_{\text{frac}} = \frac{\text{POC}}{\text{SOC}} \times 100.$$

POC is the content of POC ($\text{g} \cdot \text{kg}^{-1}$), $\text{POC}_{\text{particle}}$ is the content of SOC measured in particulate matter ($\text{g} \cdot \text{kg}^{-1}$), f_{mass} is the mass fraction of particulate matter in soil (%), POC_{frac} is the distribution ratio of POC (%), and SOC is the content of SOC ($\text{g} \cdot \text{kg}^{-1}$).

2.3.2.2 Infrared spectroscopy of SOM

Soil aggregates were separated by wet sieving into three fractions: $>2 \text{ mm}$, $2\text{--}0.053 \text{ mm}$, and $<0.053 \text{ mm}$. The ground soil powder and potassium bromide carrier were uniformly mixed at a mass ratio of 1:150, and a semi-transparent pellet was prepared by compression molding. Organic functional groups were characterized using Fourier-transform infrared (FT-IR) spectroscopy (Nicolet-6700). Spectra were collected over the range of $4,000\text{--}400 \text{ cm}^{-1}$ with a resolution of 4 cm^{-1} and 16 cumulative scans.

2.4 Data analysis

The study area map was created in ArcGIS 10.2. One-way analysis of variance (ANOVA) was performed on soil properties and carbon fractions using Origin, and Tukey's HSD was used for post-hoc multiple comparisons ($p < 0.05$). In FT-IR spectroscopy,

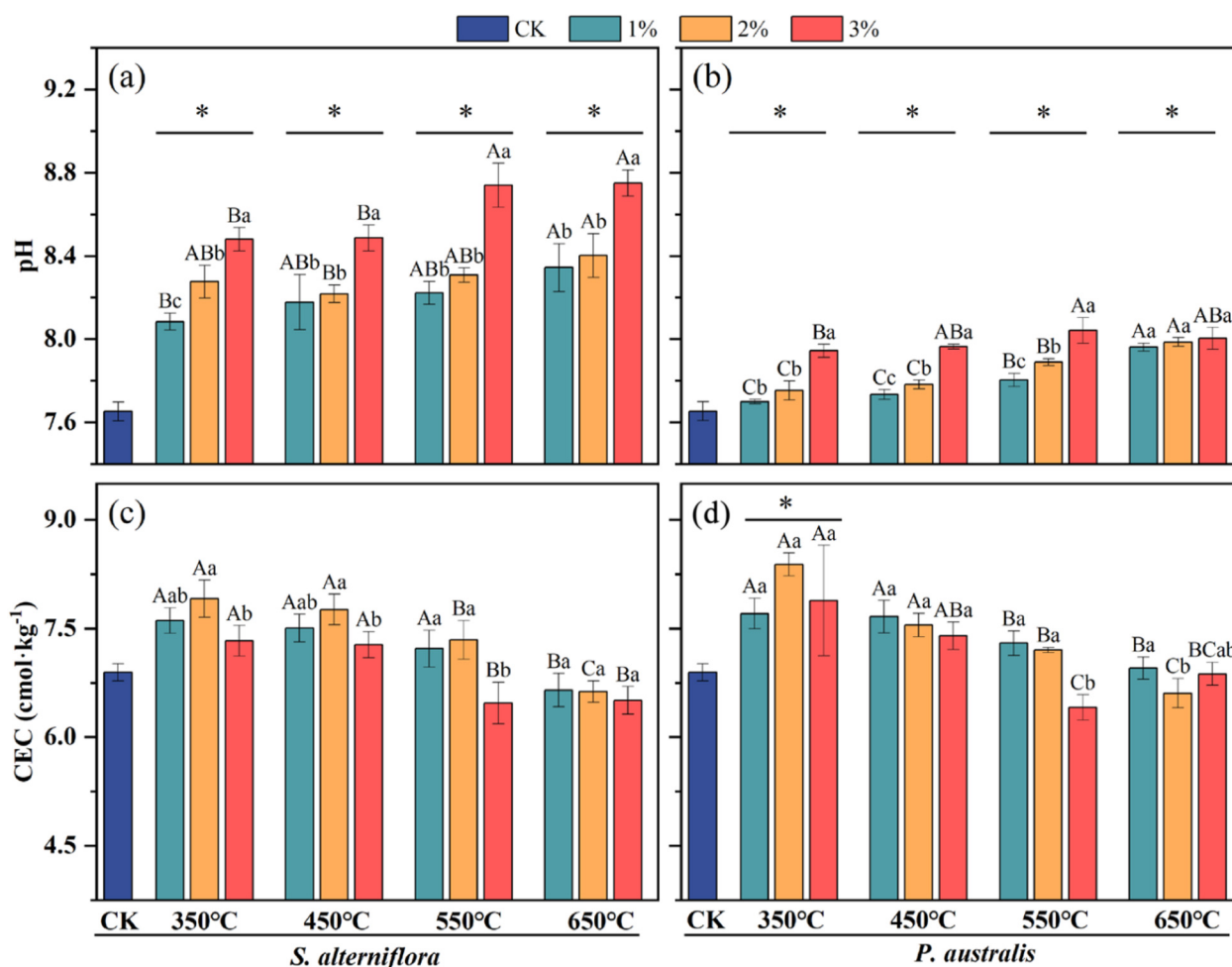


FIGURE 2

Effects of *S. alterniflora* (a,c) and *P. australis* (b,d) biochars on soil pH and CEC. * indicates significant differences between all treatments within a group and the control ($p < 0.05$). Different lowercase letters indicate significant differences among different addition treatments at the same pyrolysis temperature ($p < 0.05$). Different uppercase letters indicate significant differences among pyrolysis temperature treatments at the same addition ($p < 0.05$).

the area under an absorption band is proportional to the abundance of the corresponding functional group. Therefore, functional groups were quantified by integrating these characteristic bands. After baseline correction in Origin, the area of each characteristic absorption band was integrated within its specific wavenumber range between 3,200 and 900 cm^{-1} . The relative integrated area was used to represent the relative abundance of different functional groups. Finally, correlations between soil properties and carbon components were examined through correlation analysis.

3 Results

3.1 Effects of biochar on pH and CEC of salt marsh soil

Both biochars significantly increased soil pH ($p < 0.01$) (Figure 2). At the same temperature and addition amount, soil pH was higher under SBC than under PBC. The highest soil pH values (8.74 and 8.75)

were observed with 3% SBC at 550 °C–650 °C. At the same temperature, soil pH was lowest with the 1% addition amount. Under the same addition amount, soil pH increased with increasing pyrolysis temperature for both biochars.

For CEC, PBC had a more pronounced effect on enhancing CEC. The effect of SBC was better than that of PBC only at 450 °C–550 °C and 2% addition amount.

3.2 Effects of biochar on nitrogen and phosphorus of salt marsh soil

3.2.1 Effects of biochar addition on TN, NH_4^+ , and NO_3^- of salt marsh soil

Both biochars increased soil TN, NH_4^+ , and NO_3^- (Figure 3). The enhancing effect was generally more pronounced for PBC than for SBC. Compared to the control group (CK), the PBC addition increased soil TN, NH_4^+ , and NO_3^- by 0.01%–0.05%, 2.7–21.7 $\text{mg}\cdot\text{kg}^{-1}$, and 0.5–1.8 $\text{mg}\cdot\text{kg}^{-1}$, respectively.

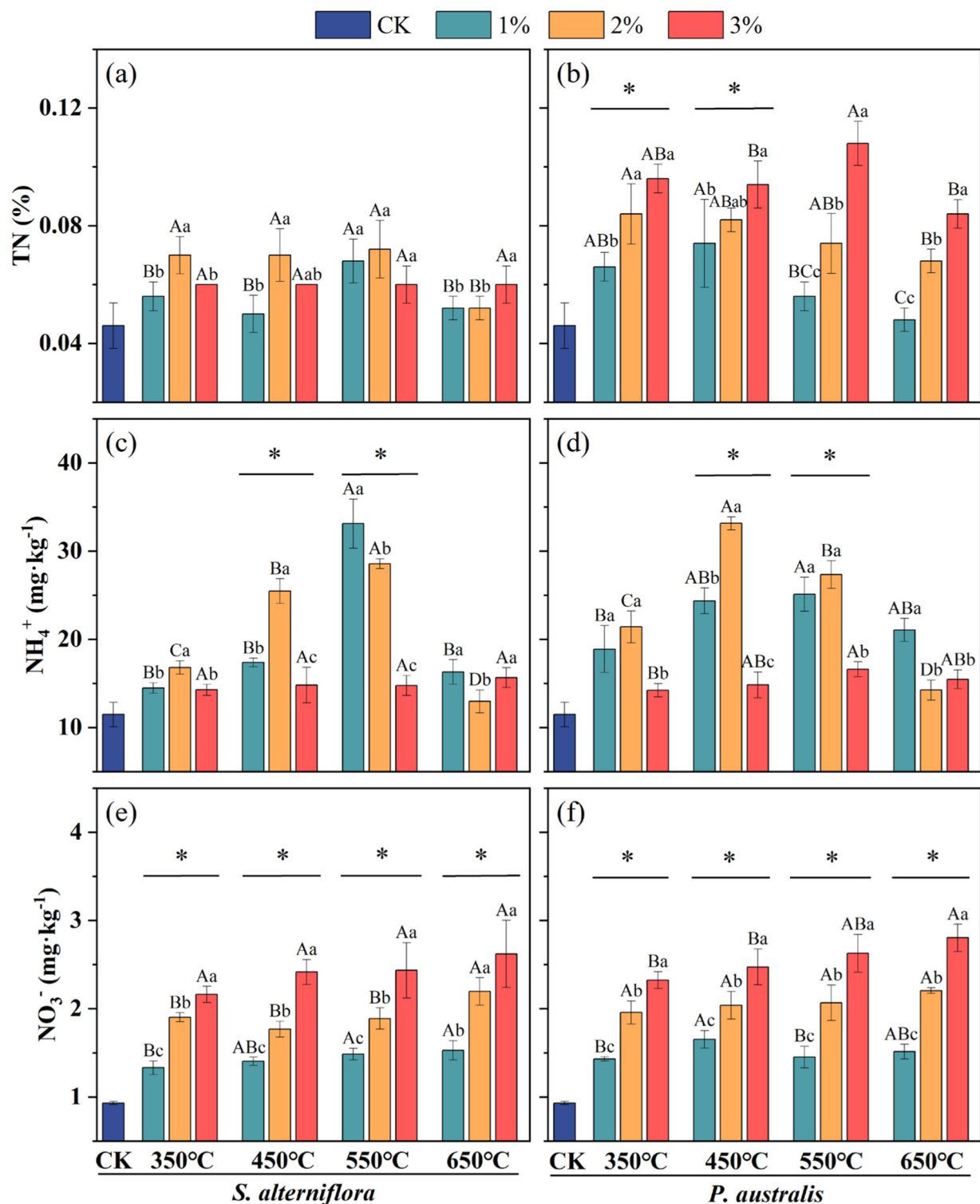


FIGURE 3
Effects of *S. alterniflora* (a,c,e) and *P. australis* (b,d,f) biochar on soil TN, NH_4^+ , and NO_3^- .

The effects of SBC and PBC on soil TN differed markedly. SBC had little to no effect on soil TN, with no significant difference from the CK. In contrast, PBC had a stronger effect on TN, and soil TN increased with increasing addition amount. At pyrolysis temperatures of 350 °C–450 °C, TN levels in

all PBC treatments were significantly higher than that of the CK ($p < 0.05$).

At 350 °C and 450 °C, soil NH_4^+ in response to both biochars first increased and then decreased with increasing addition amounts, with the peak value observed at 450 °C under the 2% addition

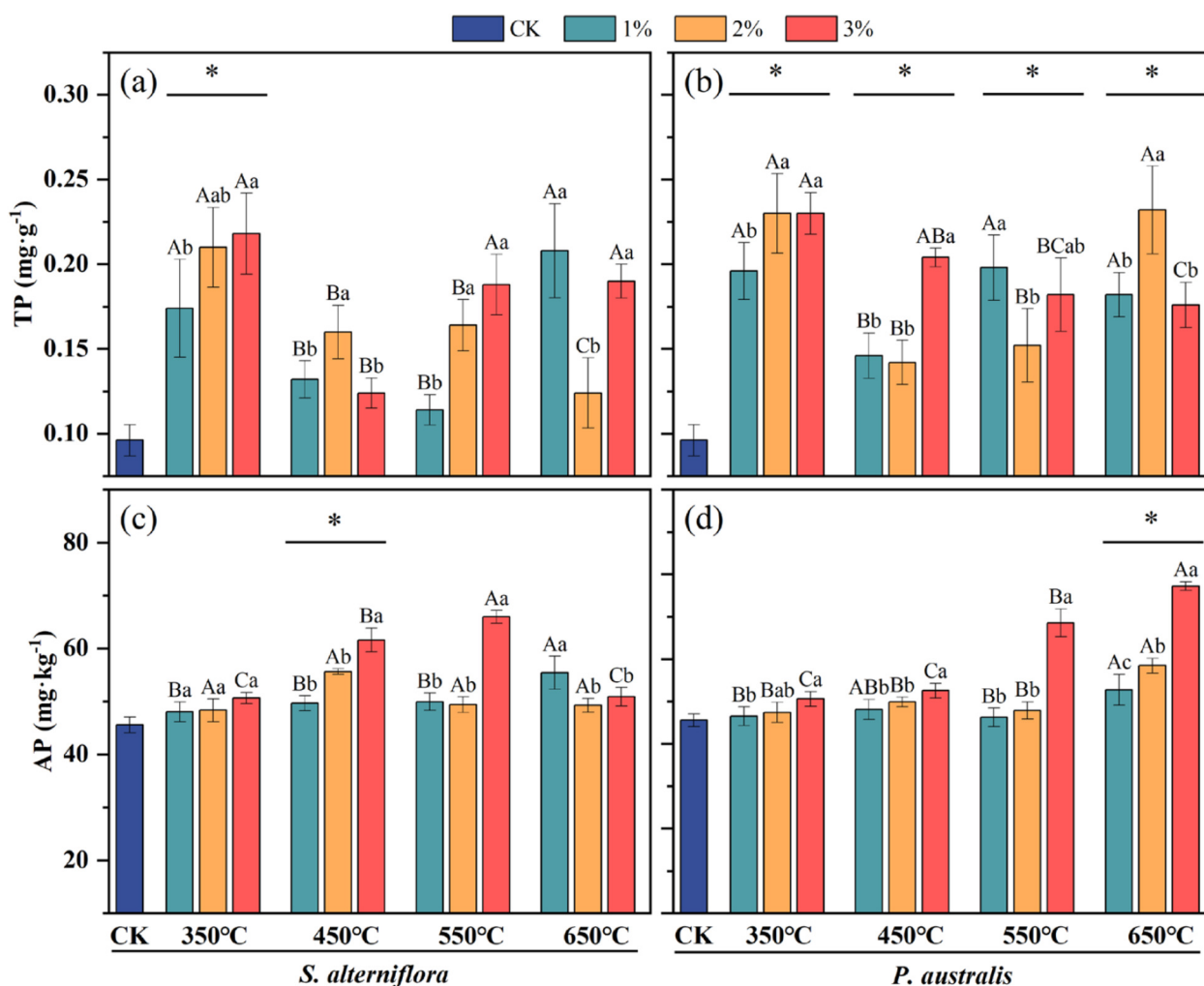


FIGURE 4
Effects of *S. alterniflora* (a,c) and *P. australis* (b,d) biochars on soil TP and AP.

amount. In contrast, at 650 °C, NH_4^+ levels showed little variation with different addition amounts. Only at 450 °C and 550 °C, the addition of different amounts of two biochars significantly increased soil NH_4^+ .

Overall, both biochars considerably affected soil NO_3^- . At the same pyrolysis temperature, NO_3^- increased with increasing addition amount. However, the same addition amount, the effect of pyrolysis temperature was minimal ($p > 0.05$).

3.2.2 Effects of biochar addition on TP and AP of salt marsh soil

Both SBC and PBC increased soil TP and AP (Figure 4), with TP showing a more marked response. At 350 °C, 1%–3% biochar significantly increased TP by 81.0%–126.8% (SBC) and 103.9%–139.3% (PBC), respectively, compared with the CK ($p < 0.01$).

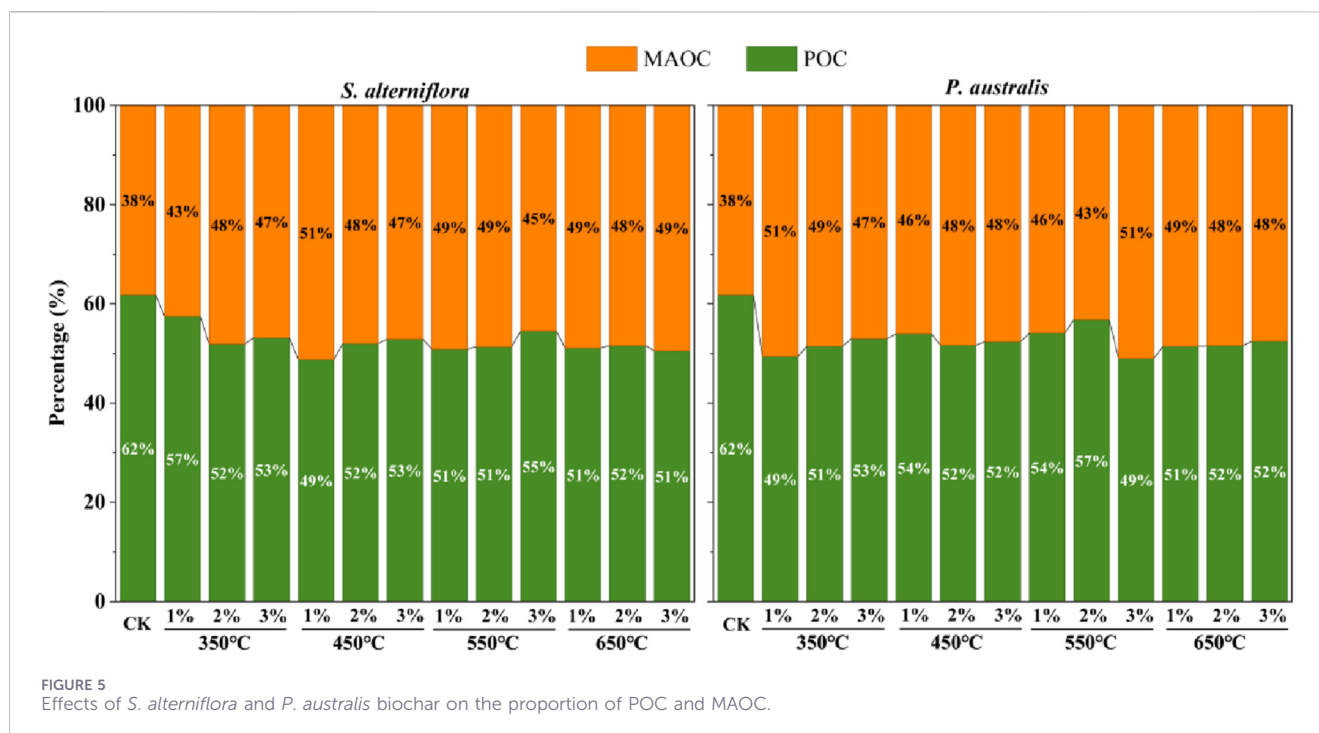
For soil AP, the highest values were consistently recorded at the 3% biochar addition, although the corresponding pyrolysis temperatures differed. Among SBC treatments, those pyrolyzed at 450 °C and 550 °C exhibited the highest AP values (61.6 and 66.0 mg kg⁻¹, respectively). In contrast, PBC produced at 550 °C

and 650 °C yielded the highest AP, while all other treatments induced only marginal changes.

3.3 Effects of biochar addition on soil carbon

3.3.1 Effects of biochar addition on the ratio of POC and MAOC

Both biochars significantly changed SOC composition (Figure 5), decreasing the proportion of POC while increasing that of MAOC. This shift was strongly influenced by pyrolysis temperature. Compared with the CK (38.02%), the MAOC proportion increased to 43.2%–51.2% following the addition of SBC and PBC. At 450 °C, 1% SBC addition significantly increased MAOC, reaching a level 34.1% higher than that in the CK, while PBC achieved a comparable improvement at 350 °C with 1% addition. Pronounced shifts in MAOC and POC fractions occurred at 350 °C–550 °C. However, at 650 °C, the addition amount and biochar type had little effect, resulting in stable MAOC proportions between 48% and 49%.



3.3.2 Effects of biochar addition on POC and MAOC contents

Both SBC and PBC significantly increased soil POC and MAOC contents ($p < 0.05$) (Figure 6). After the addition of SBC and PBC, POC increased to 1.33–3.10 times and 1.44–4.09 times that of the CK, respectively. PBC generally induced a greater increase in POC than SBC. In contrast, MAOC responded more strongly to SBC (1.63–3.32 times) than to PBC (1.62–3.12 times). Both POC and MAOC contents increased with increasing biochar addition amount ($p < 0.05$), but did not consistently increase with increasing pyrolysis temperature.

3.3.3 Effects of biochar addition on the structural characteristics of MAOC and POC

Despite variations in biochar materials, pyrolysis temperature, and addition amount, the FT-IR spectra showed high similarity (Figure 7). The carbohydrate-related peak at $1,033\text{ cm}^{-1}$ was dominant in all spectra, with its band intensity significantly higher than that of other characteristic peaks. In soils amended with SBC and PBC, their relative proportions reached 32.1%–40.7% and 33.3%–45.5%, respectively. The peak at $1,633\text{ cm}^{-1}$, assigned to conjugated C=C stretching, was the second most prominent, followed by those for aliphatic C–H stretching at $2,920\text{ cm}^{-1}$ and O–H stretching at $3,427\text{ cm}^{-1}$. Nevertheless, the relative intensities of these characteristic peaks differed among treatments.

For POC components, the addition of both SBC and PBC reduced the relative abundance of alcohols and phenols (Figure 8). Under high temperature and high addition amount, PBC induced a more pronounced reduction, with a maximum decrease of 46.2%. In addition, at a high addition level of 3%, PBC also significantly reduced the relative abundance of

polysaccharides, aliphatics, carbohydrates, disubstituted benzenes, and cis-olefins. In contrast, SBC addition increased the relative abundance of these functional groups. At lower addition amounts (1%–2%) and pyrolysis temperatures (350 °C–550 °C), both biochars had minimal effects on these functional groups. At 650 °C, the relative abundances of polysaccharides, aliphatics, disubstituted benzenes, and cis-olefins were higher under PBC than under SBC addition, whereas aromatics showed the opposite trend.

For MAOC components, both biochars generally decreased the relative abundance of alcohols, phenols, and carbohydrates. In contrast, SBC increased the relative abundance of polysaccharides and aliphatics. However, at 650 °C, after the addition of 2% and 3% PBC, alcohols, phenols, polysaccharides, and aromatics decreased significantly, whereas aliphatics increased considerably. This increase in aliphatic compounds was particularly pronounced for disubstituted benzenes and cis-olefins, which reached 2.2 times and 4.4 times the CK level, respectively, at 550 °C with a 3% PBC addition.

3.4 Exploration of the relationship between soil properties and carbon components

Correlation analysis revealed that POC and MAOC were positively correlated with pH, NO_3^- , and AP ($p < 0.01$) under both biochar treatments (Figure 9). Moreover, TN was positively correlated with POC and MAOC under PBC addition ($p < 0.01$). The relationships between soil properties and organic carbon functional groups differed between biochars. For PBC, pH exhibited significant correlations with functional groups. However, for SBC within MAOC components, pH was positively correlated only with aliphatic groups ($p < 0.01$). In contrast, CEC showed stronger correlations with functional groups under SBC

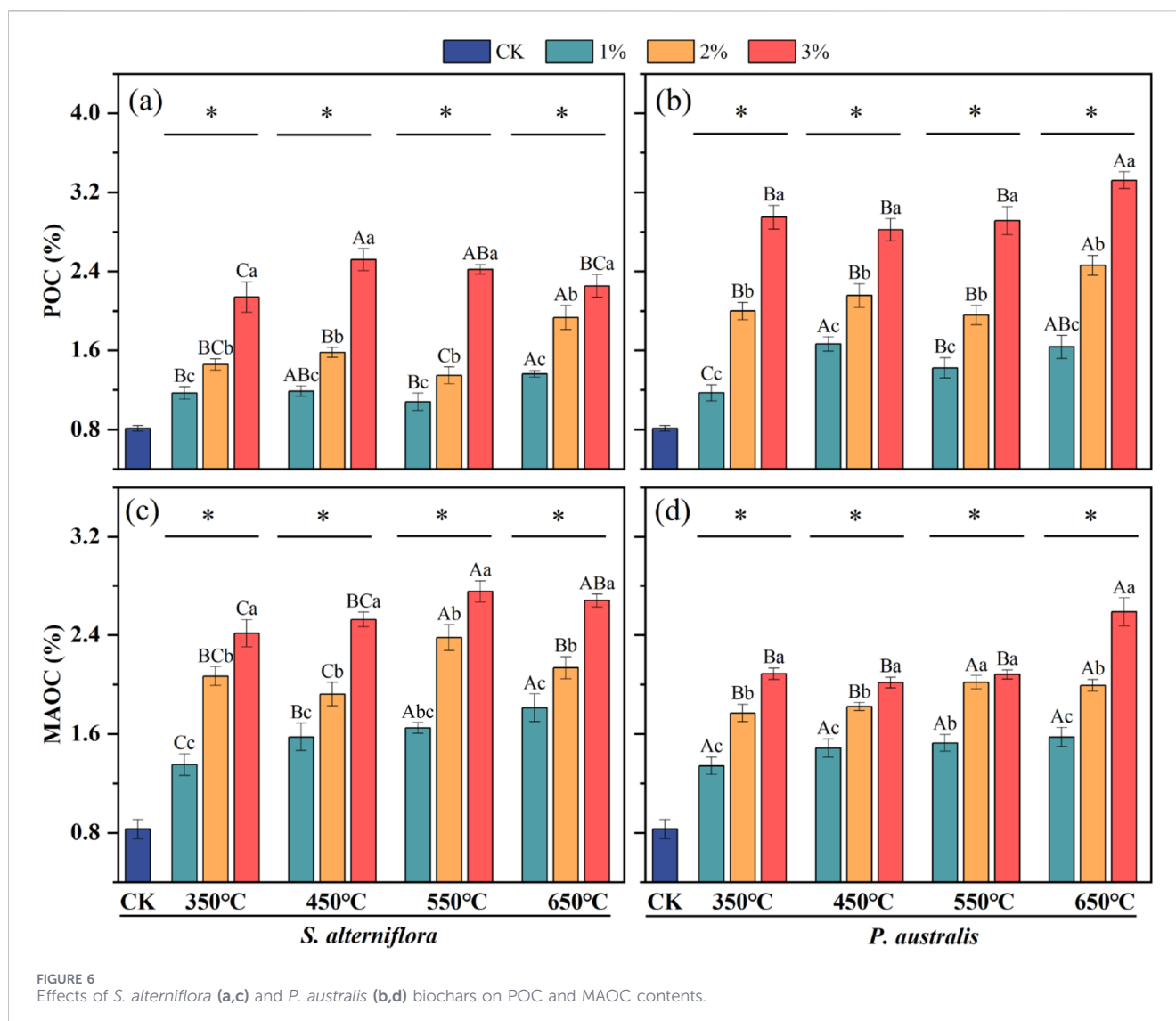


FIGURE 6
Effects of *S. alterniflora* (a,c) and *P. australis* (b,d) biochars on POC and MAOC contents.

addition than under PBC addition. For nitrogen (N) and phosphorus (P), after adding PBC, P had a greater impact on functional groups, especially AP ($p < 0.05$). In contrast, no significant correlations were observed between P and functional groups following SBC addition ($p > 0.05$).

4 Discussion

4.1 Effects of biochar addition on soil physicochemical properties

The efficacy of biochar in improving soil properties is governed by its materials, pyrolysis temperature, and addition amount (Ahmad et al., 2022; Chen et al., 2022). Biochar with high ash content tends to be more alkaline (Sun X. et al., 2023). SBC is alkaline and contains higher levels of base cations (Na^+ , K^+ , and Ca^{2+}), which explains its strong effect on increasing soil pH. In contrast, Zheng et al. (2018) reported only a slight pH change after adding peanut-shell biochar ($\text{pH} = 9.43$) to saline-alkali soil,

possibly due to differences in raw materials and organic acid secretion from halophyte roots. However, since salt marsh soils are saline with high pH, excessive pH can adversely affect soil microorganisms and benthic animals (Feng and Deng, 2025). However, PBC, which contains a greater proportion of organic components, including more C, H, and N elements (Wang et al., 2021), and richer oxygen-containing functional groups such as carboxyl and hydroxyl groups (Chen, 2021), increased pH moderately. The increase in soil CEC after biochar addition can be attributed to its oxygen-containing functional groups, such as OH (Figure 7) (Zheng et al., 2018). In addition, biochar contains nutrients (N and P) that can slowly release into the soil, directly increasing their availability (Zhang et al., 2016); however, this release process is affected by raw materials, pyrolysis temperature, and addition amount (Glaser and Lehr, 2019). In acidic soils, biochar can increase soil pH, reduce P fixation by Fe, Al, and Ca, and promote the transformation of P to soluble forms, thereby improving AP availability (Neenu et al., 2023). However, in alkaline soils, high pH can cause the formation of insoluble phosphate precipitates with Ca^{2+} and Mg^{2+} (Chang et al., 2025), and such immobilized P can only

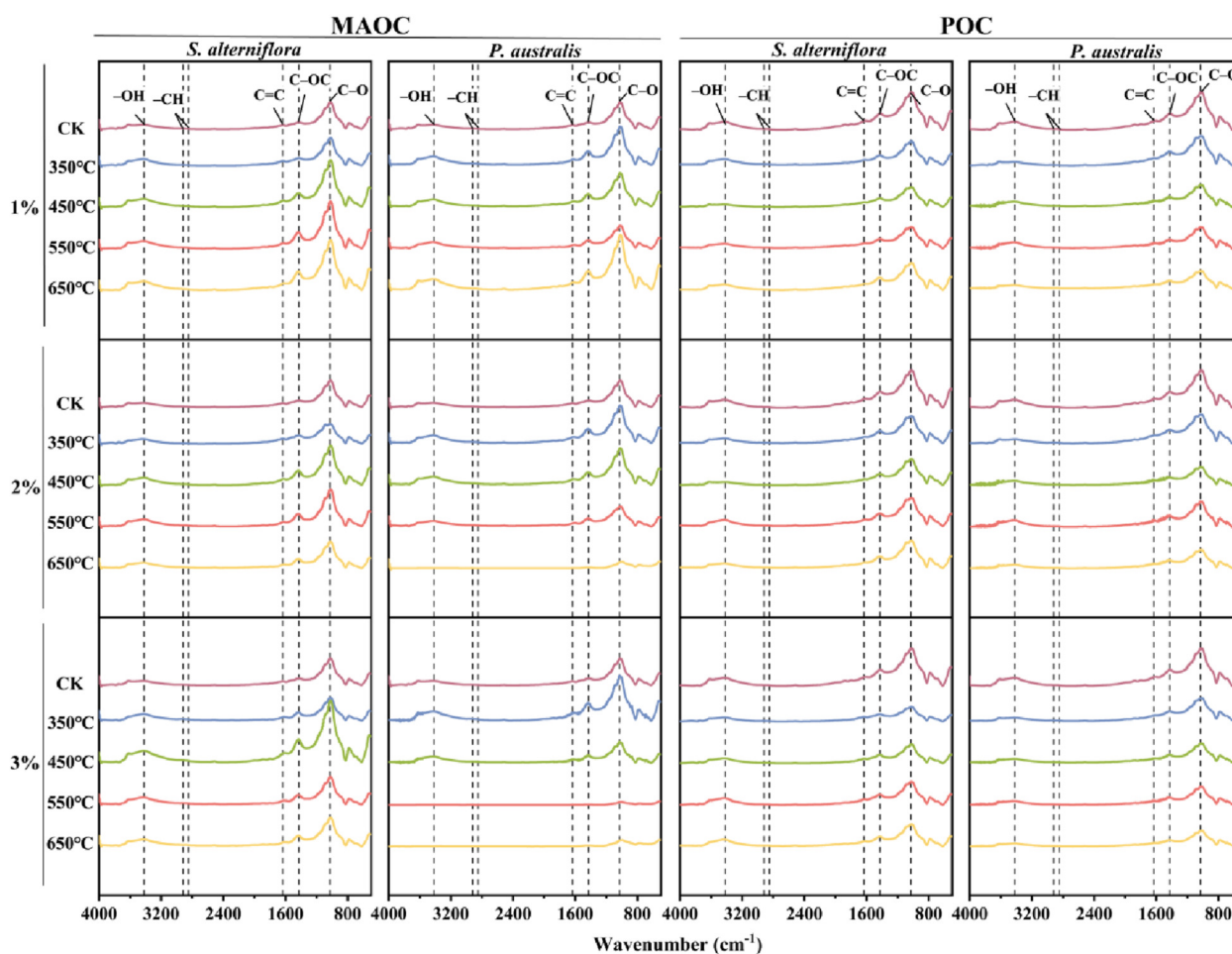


FIGURE 7
Effects of *S. alterniflora* and *P. australis* biochars on MAOC and POC infrared spectra.

be released after long-term weathering or rhizosphere acidification. This mechanism explains why both biochars limited AP improvement in this 4-month experiment. PBC had a more pronounced effect on enhancing CEC, thereby improving soil nutrient retention capacity. Therefore, soils amended with PBC tended to have higher levels of N and P.

Higher pyrolysis temperatures increase the degree of carbonization and ash content of biochar (Wang et al., 2021), leading to significantly higher pH (Wang et al., 2015; Khater et al., 2024). In this study, both biochars showed increased pH with increasing pyrolysis temperature, consistent with enhanced carbonization and ash content. At low pyrolysis temperatures, biochar retains more oxygen-containing functional groups (e.g., carboxyl and phenolic hydroxyl groups), which are key contributors to its CEC. However, these functional groups degrade at high temperatures, leading to reduced CEC (Domingues et al., 2020). Thus, at higher pyrolysis temperatures, although biochar induces a greater increase in soil pH, its contribution to CEC is limited, owing to the loss of these exchangeable functional groups.

Pyrolysis temperature also affects the chemical forms and bioavailability of nutrients in biochar. With the increase in temperature, P in biochar tends to transform into insoluble

forms, making little contribution to AP (Glaser and Lehr, 2019). In contrast, P in biochar produced at low-to-medium temperatures is more easily released and utilized by plants (Xing et al., 2024) because residual organic or soluble inorganic P in low-temperature biochar can be easily released into the soil. At high pyrolysis temperatures, P may form stable minerals with Ca and Mg (Dai et al., 2016). N content in biochar also decreases sharply at high pyrolysis temperatures due to volatilization. Biochar produced at lower temperatures contains more labile C and N, which can release nutrients through short-term microbial decomposition. Pyrolysis at 350 °C for 1 hour did not achieve complete carbonization of SBC, resulting in underdeveloped micropore structures (Qiu et al., 2018). This limitation reduces SBC's ability to retain soil nutrients over the long term and increases the risk of moisture loss. Therefore, it is necessary to control the pyrolysis temperature to improve soil nutrient availability.

Generally, soil properties improve with increasing addition amounts (Ahmad et al., 2022; Domingues et al., 2020). In this study, soil pH and CEC increased with higher biochar addition. However, excessive addition can induce negative effects, including aggravated soil alkalinity and nutrient immobilization (Wang et al., 2022). High-temperature SBC increased soil pH to nearly 8.8, which



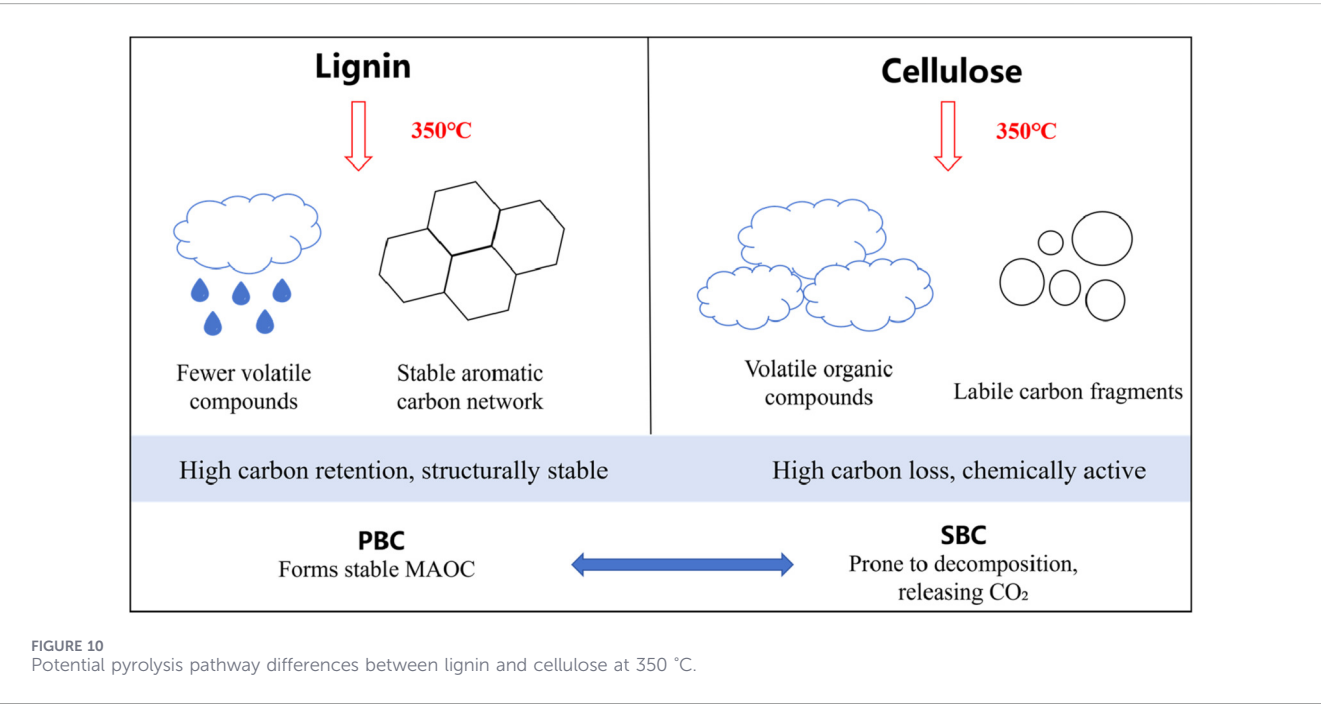
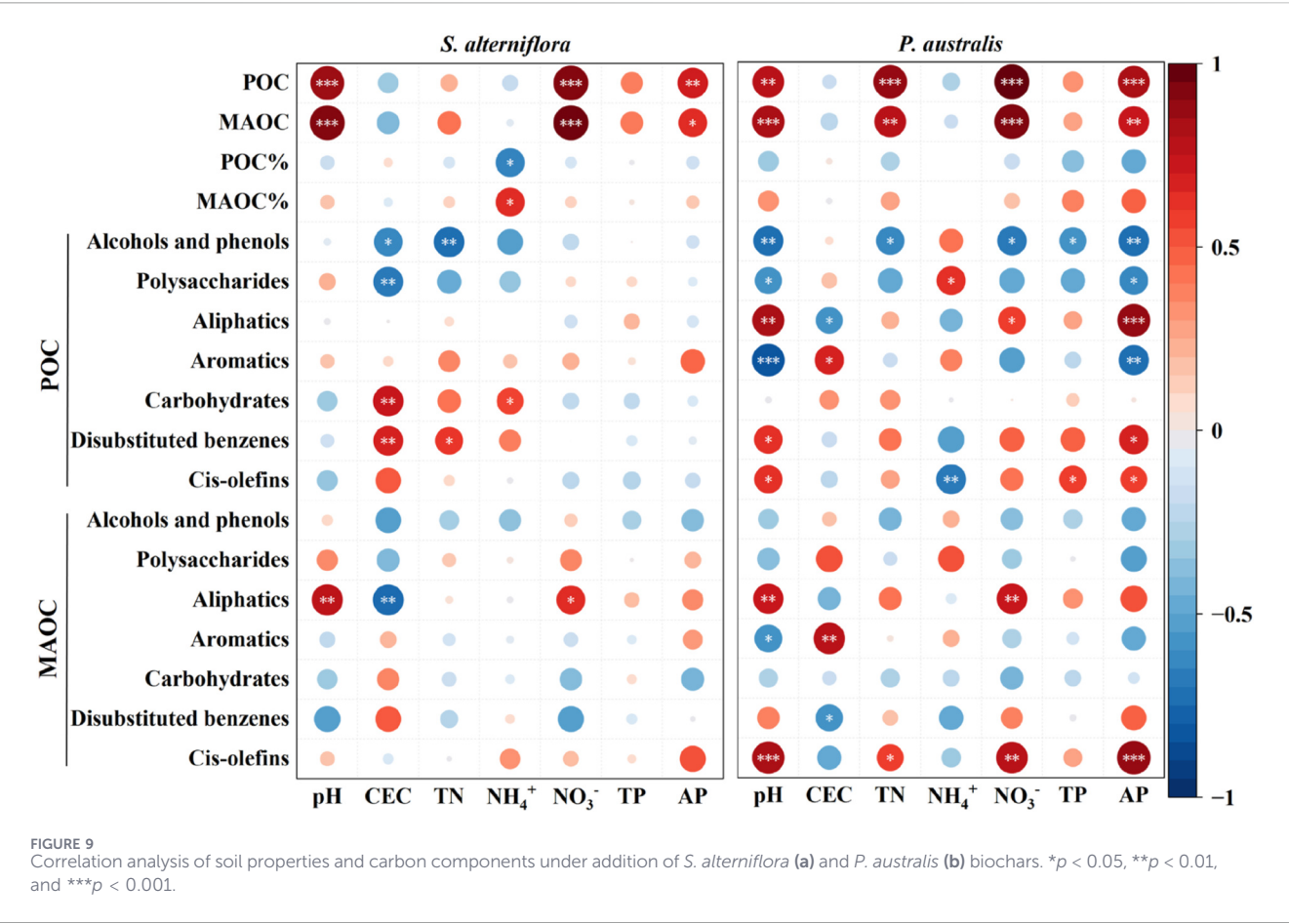
could aggravate alkalization in salt-marsh soils. Regarding nutrient availability, excessive biochar can fix or precipitate nutrients. Xing et al. (2024) also found that when biochar increased soil pH beyond neutrality, excess P tended to form insoluble forms. For N, appropriate biochar addition helped reduce N leaching and increase soil TN (Müller et al., 2013). It has been reported that the high C/N ratio of biochar may stimulate microbial N immobilization, temporarily reducing soil inorganic N. Simultaneously, for soils amended with SBC, the soil pH approached (at 350 °C–450 °C) or exceeded 8.5 (at 550 °C–650 °C) under the high addition amount of 3%. When the pH exceeds 8.5, NH_4^+ is rapidly converted to ammonia gas (NH_3) and lost to the atmosphere via volatilization. This process explains the observed decrease in soil NH_4^+ under the high addition amount (3%) (Figure 3c). Therefore, special attention must be paid to pH management during biochar addition to prevent excessive soil alkalization and disruption of nutrient dynamics caused by over-application.

4.2 Effects of biochar addition on POC and MAOC

POC and MAOC are two components of SOC (Lavalley et al., 2020). POC is mainly derived from partially decomposed plant residues. It has a rapid turnover rate and is relatively unstable

(Yue et al., 2022). In contrast, MAOC originates primarily from microbial products and dead residues and can persist stably in soil over the long term (Angst et al., 2021). Consequently, the content and proportion of MAOC serve as key indicators of soil carbon stability (Li et al., 2025). Previous studies have shown that biochar addition markedly affects the distribution and accumulation of POC and MAOC in soil (Zhang et al., 2023). We found that both SBC and PBC significantly increased soil MAOC content while reducing the proportion of POC. This shift occurred because biochar promoted the adsorption of SOC by soil mineral particles and enhanced the stability of SOC (Lei et al., 2024).

High-temperature biochar is generally more conducive to long-term SOC preservation (Chen et al., 2019; Wang et al., 2021). As pyrolysis temperature increases, aromatic carbon content increases, the pore structure develops, and specific surface area and porosity tend to increase (Tomczyk et al., 2020). These changes enhance biochar stability and promote the binding of SOC with minerals (Liu et al., 2016). However, the optimal conditions for carbon stabilization differed between SBC and PBC. This disparity can be attributed to their distinct chemical compositions. *P. australis* is richer in hemicellulose and lignin, while *S. alterniflora* consists predominantly of cellulose and hemicellulose, resulting in a higher lignin-to-cellulose ratio in *P. australis* (Yue et al., 2022). Consequently, during pyrolysis, *P. australis* is more prone to form stable aromatic carbon structures at lower temperatures (350 °C)



(Figure 10), whereas a larger fraction of carbon in *S. alterniflora* is retained and only released at higher temperatures (450 °C). Furthermore, the thermal decomposition of lignin and hemicellulose generates oxygen-containing functional groups (e.g., –OH and –COOH), which directly enhance the CEC and cation retention capability of PBC (Figure 2), thereby facilitating MAOC accumulation even at lower pyrolysis temperatures. Thus, PBC addition more effectively promotes soil carbon stabilization. Nevertheless, direct evidence for the chemical transformation pathway that links chemical composition to aromatic-carbon formation (e.g., solid-state ^{13}C NMR or SEM images) remains to be provided in future studies. Methodologically, although particle-size fractionation may inadvertently include fine biochar fragments (<0.53 μm) in the MAOC fraction, we minimized their influence by baseline-correcting against the control (no biochar). For greater precision, future work could verify the MAOC fraction through isotopic analysis or by combining particle-size separation with density-based fractionation.

Biochar addition not only altered the ratio of POC and MAOC but also changed the molecular structure and stability of SOC. After biochar addition, the functional group composition of both soil POC and MAOC changed significantly. Although the characteristic absorption peaks were consistent, their relative abundances differed significantly. The carbohydrate-related absorption peak dominated all spectra, representing a key SOC fraction. Within MAOC, polysaccharides showed the most pronounced increase following biochar addition. This response is attributed to the fact that both *S. alterniflora* and *P. australis* are gramineous plants rich in cellulose and hemicellulose. During low-temperature pyrolysis, abundant partially aromatized polysaccharide fragments and long-chain aliphatic moieties are retained on the biochar surface (Zhu et al., 2021), which can be slowly released into the MAOC pool. The increase in carbohydrates and polysaccharides indicates that the addition of both biochars may activate microbial activity in soil, prompting the conversion of labile carbon into protected MAOC. However, carbohydrates and polysaccharides are chemically less stable than aromatic substances. Nevertheless, the increased abundance of aliphatic groups within the MAOC fraction indicates a shift in organic carbon from an “easily degradable” to a “more stable” state.

In addition, we found that the pyrolysis temperature and addition amount of PBC can regulate the chemical properties of MAOC. At high temperatures (550 °C and 650 °C) and a high addition amount (3%), PBC-amended soils showed lower relative abundances of phenols, polysaccharides, and other oxygen-rich groups, whereas disubstituted benzenes and cis-olefins increased. This pattern can be explained by two complementary mechanisms. First, high-temperature biochar usually has low content of soluble OM and labile carbon, which may limit microbial activity (Li S. et al., 2019), thereby reducing the microbial production of extracellular polysaccharides, alcohols, and phenols. Second, the inherent stability of the compounds differs: disubstituted benzenes possess a highly fused aromatic structure and can form very stable chelates with Fe–Al oxides (Kung and McBride, 1991), whereas polysaccharides and aliphatic compounds are prone to decomposition at high temperatures (Zhu et al., 2021). Therefore, high-temperature, high-addition PBC promotes a shift in MAOC chemistry toward higher aromaticity.

4.3 Environment implications and prospects

PBC produced a more pronounced improvement in salt marsh soil than SBC, increasing the proportion of MAOC and promoting SOC stability. Although less effective than PBC, SBC still contributed to soil improvement and carbon stabilization. As an invasive plant currently subjected to large-scale eradication, *S. alterniflora* produces substantial straw biomass, offering a promising material for resource utilization. In this study, we provide a scientific basis for optimizing biochar addition strategies in the future. However, this study was conducted under controlled laboratory conditions with constant temperature and moisture, whereas natural salt-marsh environments are subject to dynamic field factors such as fluctuating temperature, moisture, tidal, salinity, and redox conditions. At the same time, the 4-month experimental period may not fully capture long-term effects. Therefore, future work should validate these findings and elucidate the underlying mechanisms through long-term field trials under realistic conditions.

5 Conclusion

Pyrolysis temperatures and addition amounts of biochar affected soil improvement and C stabilization in coastal salt marsh soil. Both SBC and PBC significantly increased soil pH and CEC. However, the excessive pH increase induced by SBC may aggravate soil alkalization and NH_4^+ loss. Both biochars also promoted the accumulation of N and P in soil. Under the 3% addition, TN, NO_3^- , and AP increased most significantly, and higher addition levels were more conducive to improving soil nutrient supply capacity. Both biochars (especially at high addition and temperature) considerably promoted MAOC accumulation and SOC stability while decreasing the proportion of POC. Although biochar addition did not considerably change the types of functional groups in SOC, it significantly altered their relative abundance. In the future, SBC and PBC hold potential for improving coastal salt marsh soil and carbon stabilization. PBC showed a more pronounced improvement in soil quality and carbon stabilization, especially when produced at low-to-moderate temperatures and applied at moderate addition levels. However, these potential benefits require validation under field conditions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LiX: Formal analysis, Methodology, Investigation, Writing – original draft. SG: Methodology, Writing – original draft, Investigation. LuX: Writing – original draft, Investigation, Methodology. LaJ: Writing – original draft, Methodology, Investigation. ZW: Methodology, Writing – original draft, Investigation. LJ-e: Project administration, Writing – review and editing, Conceptualization, Supervision, Investigation. HJ: Writing – review and editing, Methodology. XS:

Writing – review and editing, Methodology. WK: Investigation, Writing – original draft, Methodology. SM: Methodology, Investigation, Writing – original draft. BJ: Investigation, Methodology, Writing – original draft.

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