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Research article

Multi-source biochar: Effects on composting humification, soil properties and plant growth

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ABSTRACT

Amid rising organic waste pressures, biochar derived from thermochemical conversion of biomass has emerged as a promising tool for enhancing compost quality and promoting sustainable soil management. This study evaluated five biochars derived from kitchen waste, pig manure, sewage sludge, distillers' grains, and biogas residue for their effects on compost performance, humification, and the soil-plant system. Composting and pot experiments were conducted to evaluate humification, soil nutrient availability, and plant responses. Results showed that biochar feedstock strongly affected composting humification process. Biogas residue biochar (BRB), with the highest specific surface area (26.48 m^2 g^{-1}), significantly enhanced compost maturity, particularly increasing the humification index by 3.72-fold. Parallel factor analysis indicated that BRB significantly enhanced the structural complexity of humus, increasing the combined proportion of humic-like and fulvic-like acids by 8.26 %. Application of 8 % pig manure biochar-amended compost significantly improved soil nutrient availability (available phosphorus, 8.55-fold) and boosted plant biomass (5.89-fold). Partial least squares path modeling analysis revealed that dose-dependent benefits of composting application, with moderate doses directly enhancing root development via biochar and humic substances, while higher doses acted indirectly by improving soil nutrients and properties. These findings highlight the feedstock-specific regulatory effects of biochar on compost quality and soil improvement, offering insights for developing tailored biochar-compost products for sustainable agricultural applications.

1. Introduction

The rapid increase in organic waste generation due to urbanization, industrialization, and intensified agricultural practices has posed significant challenges for sustainable waste management and soil fertility maintenance worldwide (Mabrouk et al., 2023). Traditional disposal methods such as landfilling or open burning not only waste valuable biomass resources but also contribute to pollution and greenhouse gas emissions. As a sustainable alternative, the thermochemical conversion of organic waste into biochar has garnered increasing attention due to its ability to simultaneously mitigate waste pressure and generate high-value, multifunctional materials. Biochar is a stable, carbon-rich, and porous substance obtained through pyrolysis of diverse organic residues under limited oxygen conditions (Nidheesh et al., 2021). Biochar has attracted widespread attention in environmental remediation, carbon sequestration, and sustainable agriculture, owing to its multifunctional roles and persistent stability in soils (Chi et al., 2024).

More recently, biochar has also received increasing research attention as a value-added additive in composting systems, where it plays multifunctional roles in improving compost quality and process

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efficiency. Numerous studies have demonstrated that biochar amendment composting can significantly improve composting efficiency, accelerate humification, and yield higher-quality compost products (He et al., 2024; Liu et al., 2023). The physicochemical properties of biochar, including high surface area, oxygen-containing functional groups, cation exchange capacity, and aromaticity, make it an effective sorbent and microbial carrier during composting. Wang et al. (2014) have proved that humic substances generated can be adsorbed and retained on the biochar surface via ligand exchange and hydrophobic interactions, thereby protecting them from microbial degradation and promoting the stability of humic products during composting. Biochar improves the microbial ecology of the composting system by providing a favorable habitat for microbial colonization, enhancing oxygen diffusion due to its porous structure, and supplying labile carbon substrates by adsorbing water-soluble carbon compounds and phenolics (Godlewska et al., 2017). Liu et al. (2023) found that biochar amendment promoted humification during composting by specifically regulating fungal community and metabolic features, thereby enhancing the soil enhancement potential of organic fertilizers. The properties of biochar vary considerably with feedstock type and pyrolysis conditions, which in turn affect its performance as a compost additive. Biochars derived from wood, food waste, or manure differ in surface area, porosity, functional groups, pH, and nutrient content. Ahmad et al. (2012) reported that biochar from peanut shells pyrolyzed at 700 °C had a surface area of 448.23 m^2/g, while that from chicken manure was only 50.94 m^2/g. These differences influence composting dynamics, humification efficiency, and the quality of the final product, thereby shaping its effectiveness in soil improvement and plant growth.

Biochar not only enhances composting performance but also increases compost products functionality. It achieves this by reducing nitrogen loss and greenhouse gas emission, mitigating heavy metal mobility, and adsorbing organic pollutants to reduce their environmental toxicity. (Chen et al., 2022; He et al., 2024). Crucially, improved compost products not only provide fertilizer but also show significant potential for rehabilitating degraded soils. This positions biochar-amended compost (BAC) as an increasingly valued and effective soil amendment. Saline-alkali soils, prevalent globally and highly responsive to remediation, rank as a major constraint on agricultural productivity. Characterized by poor structure, low nutrient efficiency, and elevated sodium levels, they pose significant challenges, particularly in arid and semi-arid regions (Yuan et al., 2023). The application of organic amendments such as compost and biochar has shown promise in improving the physicochemical and biological properties of saline soils, including pH buffering, sodium displacement, soil aggregation, and enhancement of microbial communities (Dahlawi et al., 2018; Liang et al., 2021). Moreover, biochar can serve as a soil fertilizer by contributing nitrogen (N) and phosphorus (P), as well as enhancing nutrient retention (Qian et al., 2023). Nevertheless, biochar alone exhibits inadequate nutrient provisioning to fulfill plant demands (Dahlawi et al., 2018). BAC serves as a dual-functional amendment that not only addresses these nutritional limitations but also enhances nutrient bioavailability, thereby ameliorating plant growth under saline-alkaline stress conditions (Qian et al., 2023). The performance of BAC varies widely depending on the biochar feedstock source and production conditions. Manure-derived BACs tend to supply more nutrients, while woody-derived BACs contribute more to structural improvement and nutrient retention (Agegnehu et al., 2017). Zhou et al. (2023) found that straw-derived BAC significantly improved plant productivity, which was attributed to its high nutrient retention capacity and lower bioavailability of heavy metals. However, such feedstock-specific differences remain underexplored in current literature. Previous studies have primarily examined single-source biochar or isolated applications of biochar and compost, lacking integrated analysis of their combined effects on humification dynamics, soil nutrient retention, and plant response. In addition, limited attention has been paid to how different feedstock types and biochar properties influence compost-soil-plant interactions under saline-alkaline conditions.

This study aims to reveal how different biochar feedstocks influence composting performance and humification dynamics, and to evaluate the effects of BAC on saline-alkali soil properties and plant growth. Composting and pot experiments were conducted to assess compost maturity, humic substance characteristics, soil nutrient availability, and plant responses. Our findings provide insights that support the tailored application of BAC and promote their use in sustainable soil management and circular bioeconomy systems.

2. Materials and methods

2.1. Feedstock, preparation, and characterization of biochar

This study used five types of biochar, including kitchen waste biochar (KWB), pig manure biochar (PMB), sewage sludge biochar (SSB), distillers' grains biochar (DGB), and biogas residue biochar (BRB), each produced from its respective organic waste feedstock. The feedstocks for biochar production were collected from representative sources: kitchen waste and biogas residue from Organic Recycling Institute (Suzhou) of China Agricultural University, sewage sludge from Xiaojiahe Wastewater Treatment Plant in Beijing, distillers' grains from Kweichow Moutai Co. (Guizhou), and pig manure from a Beijing livestock farm. Prior to pyrolysis, the raw materials were air-dried and ground to pass through a 2-mm sieve to ensure uniform particle size distribution. All biochars were produced by a company in Xinyang, Henan Province, under pyrolysis conditions of nitrogen atmosphere, a heating rate of 10 °C/min, and a 2 h hold at 500 °C (Ippolito et al., 2020). The main physicochemical characteristics of all biochars are summarized in Table S1.

The surface morphology of biochar was imaged via high-resolution scanning electron microscopy (SEM, ZEISS GeminiSEM 300, Germany) operated at 5 kV. Biochar samples were gold-coated prior to SEM imaging. Micrographs (2k–50k × magnification) revealed detailed micro- and mesoporous structures. Porosity parameters, including specific surface area (SSA, 100–500 m^2/g), pore volume, and multimodal pore distribution (micropores and mesopores), were quantified through N_2 adsorption-desorption isotherms at 77 K using a fully automated gas sorption analyzer. Prior to analysis, biochar samples underwent vacuum degassing at 300 °C for 8 h (confirmed non-pyrolytic under this condition). Data were processed via Brunauer-Emmett-Teller (BET) and density functional theory (DFT) models.

2.2. Composting experiment and physicochemical properties analysis

The compost raw materials consisted of food waste sourced from the Institute of Organic Recycling (China Agricultural University) and sawdust obtained from a commercial wood processor in Suzhou. The properties of raw materials are shown in Table S1. The composting process with biochar amendments was conducted in 60 L reactors (detailed schematic in Fig. S1). Five treatments amended with different biochars (KWB-T1, SSB-T2, PMB-T3, DGB-T4, BRB-T5) and one control (CK, without biochar) were established. Following air-blowing pretreatment to remove surface dust and 80-mesh sieving, biochars were incorporated into composting raw materials at 10 % (w/w, dry basis) (Chen et al., 2023). The initial mixtures (15 kg per reactor) were formulated to achieve a C/N ratio of 25 with sawdust supplementation and maintained at 60 % moisture prior to biochar homogenization. Aerobic conditions were maintained at 0.3 L min^{-1}·kg^{-1} dry OM throughout the 15d composting period. Real-time temperature profiles were wirelessly recorded by embedded sensors and synchronized to a central PC. Scheduled pile homogenization and sampling occurred at intervals on days 0, 5, 7, 9, 11, 13, and 15. Samples were collected from five locations (top, middle, bottom layers) within the compost pile to ensure representativeness and minimize spatial heterogeneity, homogenized, and composited fo physicochemical and humification analyses.

Immediately after collection, samples were partitioned: one portion (250 g) was stored at 4 °C for physicochemical analysis, while the other (50 g) was preserved in liquid nitrogen vapor phase (−80 °C) served for DNA/RNA extraction.

Basic physicochemical parameters including pH value, electrical conductivity (EC), moisture content (MC), germination index (GI), and total organic carbon (TOC) were measured as described by Zhan et al. (2024).

2.3. Humus extraction and EEM-PARAFAC analysis

The extraction method of HS including HA and FA was based on the procedure of Chang et al. (2023), and the carbon content of HA and FA was determined with a TOC analyzer (TOC-L CPH, Shimadzu, Japan).

Excitation-Emission Matrix Fluorescence Spectroscopy (EEM) of humic substances (HS) was systematically performed using a calibrated Hitachi F-7000 spectrophotometer (Tokyo, Japan). Instrument parameters were optimized for HS characterization (excitation: 200–450 nm; emission: 250–550 nm; 5 nm step size), with methodology refined from standard organic matter analytical workflows (Chen et al., 2025).

2.4. Pot experiment and physicochemical properties analysis

Saline-alkali soil was collected from the topsoil layer (0–20 cm) of an experimental field in Guyuan City, Ningxia Hui Autonomous Region, Northwest China. The biochar-amended compost products obtained from the aforementioned composting experiments comprised: kitchen waste biochar-amended compost (KWBC), sewage sludge biochar-amended compost (SSBC), pig manure biochar-amended compost (PMBC), distillers' grains biochar-amended compost (DGBC), and biogas residue biochar-amended compost (BRBC). The properties of soil and compost products are shown in Table S2. The pot experiment utilized perennial ryegrass (*Lolium perenne* L.), a gramineous forage species native to Eurasian grasslands. This rapidly establishing grass, characterized by high biomass productivity and exceptional nutritional profile, was procured from rangelands in northwestern China's Ningxia Hui Autonomous Region, where it is cultivated as a high-value fodder crop.

The pot experiment was conducted in climate-controlled chambers at organic recycling institute (Suzhou) of China Agricultural University. The saline-alkali soil was first air-dried, then homogenized by passing through a 2-mm sieve. Five biochar-amended composts were incorporated into the prepared soil at 1 %, 4 %, and 8 % (w/w) application rates, with an unamended soil serving as the control (CK). Mixtures (0.5 kg soil-compost/pot) were loaded into cylindrical pots (height 10 cm, upper diameter 10.6 cm), each sown with 50 surface-sterilized ryegrass seeds. To ensure uniform compaction, each pot was gently tapped during filling to standardize soil bulk density. Pots (triplicates per treatment) were conducted in a climate-controlled chambers at 25 °C with a 16/8 h light/dark photoperiod, light intensity of 250 ± 10 μmol $m^{-2}\cdot s^{-1}$ (PPFD), and relative humidity maintained at 60 ± 5 %. To minimize positional light bias, pots were randomized daily. No supplemental fertilization was applied post-inoculation. After 60 d, plants were gently harvested, rinsed with DI water, and separated into shoots and roots. Soil samples were split into two aliquots: one for nutrient profiling (4 °C storage) and another for microbial assays (−80 °C).

Soil pH and EC were measured as in compost analysis. Available phosphorus (AP, $NaHCO_3$ extraction), alkali-hydrolyzable nitrogen (AN, HCl-H_2SO_4 hydrolysis) Available potassium (AK, NH_4OAc digestion) followed Han et al. (2024). Plant biomass was partitioned into shoots and roots. Fresh weights were recorded after deionized water rinsing and blot-drying. For dry weights, tissues were oven-dried at 70 °C to constant mass post 105 °C enzyme deactivation (30 min). Biomass data were obtained from three biological replicates per treatment. Fresh and dry weights were averaged from these replicates, and any measurement with large deviation (>5 %) was cross-checked and re-measured.

2.5. Statistics analysis

Excitation-Emission Matrix (EEM) fluorescence spectroscopy coupled with Parallel factor (PARAFAC) was implemented in MATLAB R2023a (MathWorks, Natick, MA, USA) using the DOMFluor toolbox (v1.7) following the protocol of Murphy et al. (2013). Partial least squares path modeling (PLS-PM) was implemented in R4.5.0 using the "plspm" package. Triplicate datasets were statistically evaluated through descriptive analysis in Microsoft Excel. Inter-group variations were assessed via ANOVA in SPSS Statistics v25 (IBM, Armonk, NY), with significance denoted as: ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$. Graphical visualization was implemented in Origin Pro (Origin Lab, Northampton, MA).

3. Results and discussion

3.1. Biochar characterization

Biochar derived from different feedstocks exhibited distinct surface morphologies and pore structures, which directly influence their adsorption potential. Among the five biochars, BRB and PMB exhibited more favorable surface and pore properties for adsorption. SEM revealed rougher surfaces with fine particles and pores on these biochars, whereas KWB and DGB exhibited smoother textures with blocked porosity (Fig. 1). BET analysis confirmed these observations (Table S3): BRB had the largest specific surface area (26.48 m^2 g^{-1}), while PMB showed the highest average pore diameter (12.45 nm), indicating enhanced mass transfer potential. Both displayed relatively balanced micro- and mesoporosity, in contrast to the predominantly microporous nature of the remaining biochar. The N_2 adsorption-desorption isotherms further supported this (Fig. S2), with BRB showing a Type IV isotherm with an H3 hysteresis loop, suggesting the coexistence of micro- and mesopores and the likelihood of capillary condensation within slit-like mesostructures (Kołodyńska et al., 2017). The adsorption behavior of PMB also indicated features of Type I isotherms at low relative pressures, reflecting predominant microporosity, followed by secondary mesopore filling. Overall, the structural characteristics of BRB and PMB suggest superior adsorption performance compared to the other biochar.

3.2. Biochar amendment effects on composting dynamics

3.2.1. Physicochemical properties

The temperature dynamics of composting with different biochar amendments are presented in Fig. 2a. All treatments exhibited a typical composting temperature progression, transitioning through mesophilic, thermophilic, and maturation phases. The thermophilic phase was reached between days 4 and 6, with peak temperatures ranging from 63.5 °C to 71.0 °C. T1 and T5 with high specific surface area maintained the thermophilic phase longer than CK. This effect may be attributed to their porous structures, which enhanced microbial colonization and oxygen diffusion (Li et al., 2024). Supporting this, He et al. (2019) demonstrated that biochar with larger surface area and pore volume improves gas exchange during composting, thereby promoting aerobic microbial activity. In particular, BRB (T5), with the highest specific surface area (26.48 m^2 g^{-1}) and a well-developed pore volume, more effectively sustained thermophilic conditions compared to the other treatments. A gradual cooling phase followed as microbial activity declined due to nutrient depletion. Pile turning induced a secondary temperature rise, most pronounced in T4 and T5, before temperatures steadily decreased after day 11. This temperature pattern indicates that biochar amendments, particularly in T4 and T5, not only prolonged the thermophilic phase but also may enhanced microbial resilience during the cooling phase (Yui et al., 2023). The secondary temperature rise following pile turning suggests improved oxygen availability and microbial activity, which likely facilitated further organic matter

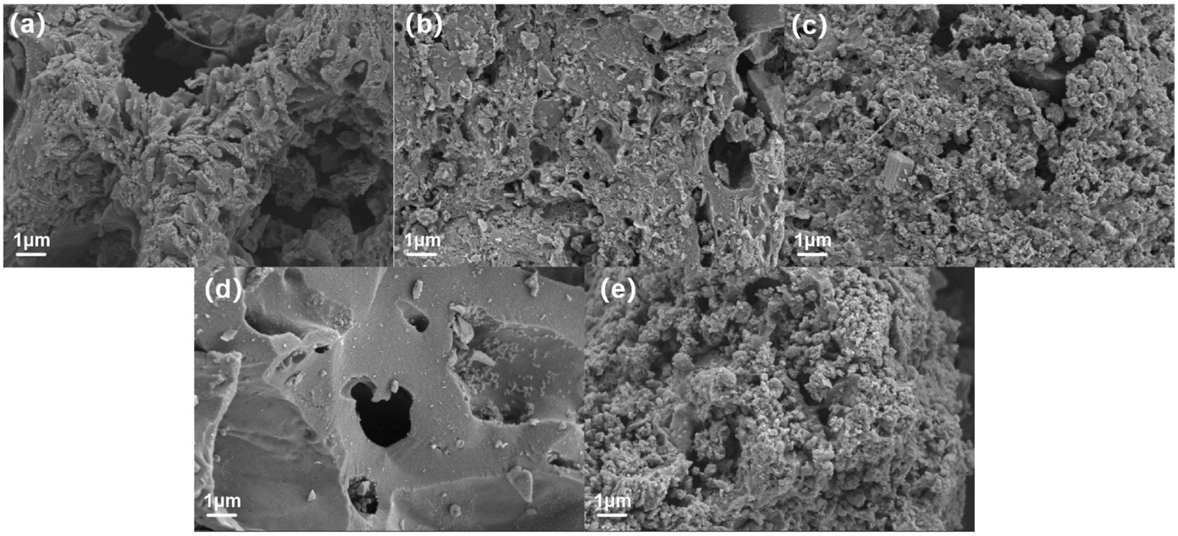

Fig. 1. Different biochar scanning electron microscope images: (a) Kitchen waste biochar, (b) Sewage sludge biochar, (c) Pig manure biochar, (d) Distillers' grains biochar, (e) Biogas residue biochar.

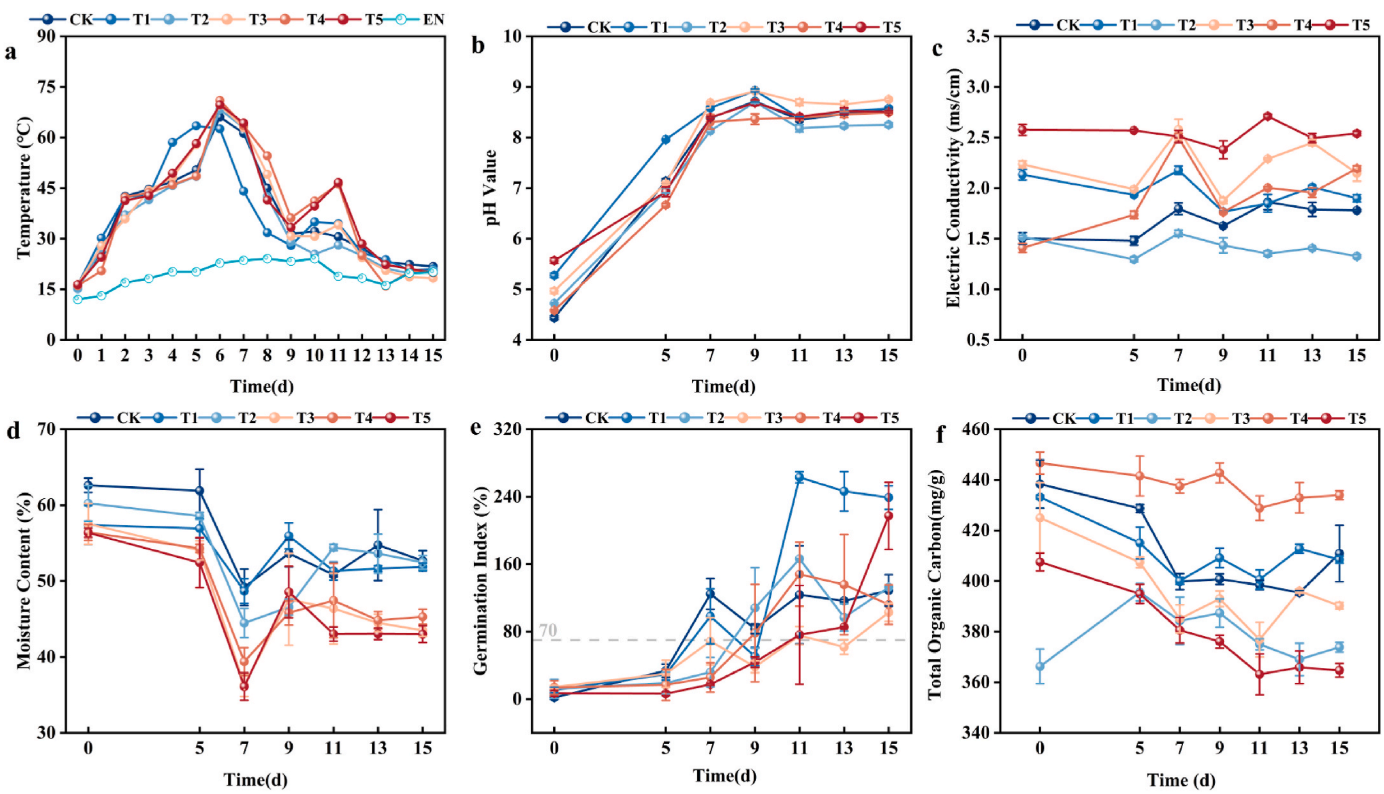

Fig. 2. Physicochemical properties during composting: (a) Temperature (EN, environmental temperature), (b) pH value, (c) Electric conductivity, (d) Moisture content, (e) Germination index, (f) Total organic carbon.

degradation and accelerated compost stabilization (He et al., 2020). These findings highlight the role of biochar in promoting composting heating up and efficient waste biotransformation (Waqas et al., 2018).

The pH trends across all treatments followed an initial increase and subsequent stabilization (Fig. 2b). At the start, all treatments exhibited weak acidity (pH 4.44–5.57). By day 7, pH values rose to around 8.50, attributed to organic acid degradation and the alkaline of biochar (Zhou et al., 2019). Post-day 11, microbial decomposition of recalcitrant organic matter led to pH stabilization, with final values ranging between 8.25 and 8.75. Electrical conductivity (EC) showed fluctuations throughout composting (Fig. 2c). Between days 0 and 15, EC varied from 1.41 to 2.58 mS cm^{-1} to 1.33–2.54 mS cm^{-1}. Throughout the process, EC remained below 4.00 mS cm^{-1}, indicating that all composts met maturity standards and could be utilized for soil improvement and crops growth (Kong et al., 2024). Moisture content dynamics are shown in Fig. 2d. During the first 7 days, moisture content declined due to evaporation facilitated by aeration (Pottipati et al., 2021). A slight increase after turning on day 7 was likely due to the redistribution of moisture from the lower layers. After day 9, the decline slowed as microbial activity decreased, reducing moisture loss (Liang et al., 2024).

The germination index (GI) increased consistently (Fig. 2e), reaching values above 70 % by day 15, indicating compost maturity (NY/T 525–2021). Treatments with KWB (239 %) and BRB (217 %) exhibited significantly higher GI values, suggesting reduced phytotoxicity and enhanced compost maturity. Total organic carbon (TOC) content declined across all treatments (Fig. 2f). By day 15, TOC levels were reduced by 2 %–11 %, with the highest reduction (11 %) observed in T5 (BRB), suggesting its superior ability to facilitate organic matter decomposition and compost mineralization. BRB's larger surface area and higher microbial carrying capacity likely accelerated microbial degradation of labile carbon fractions. In contrast, the slower TOC reduction observed in SSB and DGB suggests lower porosity and reduced microbial accessibility. Taken together, composting performance differences among the five biochars stem primarily from their differing physicochemical properties (dictated by raw material and pyrolysis conditions). Effects varied significantly by biochar, heavily dependent on specific characteristics like surface area and pore structure. These properties govern performance through distinct microbial and chemical pathways, underscoring the key role of biochar's structural and chemical properties in regulating composting kinetics and humification outcomes.

3.2.2. Humification process

HS content dynamics reflect the balance between its formation and degradation, directly influencing compost quality as a key indicator of maturity (Fig. 3a) (He et al., 2024). Throughout composting, BRB (T5) significantly enhanced HS accumulation, with a final content of 77.00 mg g^{-1}—2.15 times higher than CK—suggesting its role in promoting HS synthesis, likely due to its high surface area properties (Wu et al., 2024). The initial increase in HS content across all treatments was attributed to the positive priming effect of biochar, which stimulates activity of microorganisms to decompose organic matter by providing additional substrate and habitat (Bo et al., 2023; Qi et al., 2024). The microbial degradation of labile organic compounds into humic precursors, which polymerized into unstable humic substances (Zhang et al., 2018). However, during the thermophilic phase (days 5–7), thermophilic microbial activity intensified HS degradation, leading to a temporary decline (Gao et al., 2021). Such decline is also in line with our previous research, this may be attributed to thermophilic microorganisms rapidly mineralizing humic precursors into CO_2 and utilizing HA as a carbon source (Chang et al., 2023). Subsequent fluctuations (days 7–11) were likely driven by the dynamic interplay between FA and HA transformation (Wang et al., 2025). These findings highlight the positive priming role of biochar in stabilizing HS dynamics and enhancing compost maturation.

HA and FA dynamics during composting reflect the influence of biochar on humification processes. HA dynamics followed a similar pattern to HS (Fig. 3b). HA accumulation was most pronounced in T5, where its content reached 39.71 mg g^{-1} by the end of composting—3.3 times that of CK—indicating that significantly enhanced the formation of HA. The high porosity and adsorption properties of biochar likely contributed to this stabilization by reducing microbial accessibility to HA and minimizing its decomposition, known as adsorption protection (Bo et al., 2023). This is consistent with the BET results. Additionally, the presence of biochar facilitated the formation of HA during the heating phase, as evidenced by the peak HA content (60.23 mg g^{-1}) observed in T5. This is attributable to biochar stimulating heightened microbial activity during the initial thermophilic phase, driving accelerated decomposition of labile organic matter precursors and their subsequent transformation into HA.

FA content showed treatment-specific trends (Fig. 3c). In contrast to other treatments, the FA of T3 and T5 decreased initially (days 0–5). This likely stems from microbial utilization of readily available FA, converting it into higher-polymerized HA (Shen et al., 2024), as corroborated by the observed HA dynamics. In the later stage, the accumulation of FA in T3 and T5 likely resulted from enhanced degradation of refractory organics and the reduced conversion into HA. By the end, T5 had the highest FA content (37.29 mg g^{-1}), 1.57 times that of CK, highlighting the role of in promoting the degradation of refractory organics and FA accumulation.

Humification indices serve as key indicators for assessing the polymerization degree of HS and compost maturity (Chang et al., 2023). To evaluate the influence of biochar on humification dynamics, DP, HR, HI, and PHA were examined (Fig. S3). By the end of composting, DP in T3-T5 was 1.90, 2.78, and 2.08 times higher than CK, suggesting that PMB, DGB, and BRB facilitated FA-to-HA conversion. HR and HI exhibited similar trends, with T5 values reaching 2.43- and 3.72-fold those of CK by composting completion, demonstrating enhanced HS stabilization and structural complexity. PHA remained consistently elevated in T3-T5 compared to CK, increasing by 1.47, 1.74, and 1.53 times, confirming these biochars promoted HA formation and accelerated the humification process.

3.2.3. Humic substances formation

Three-dimensional fluorescence spectroscopy was used to track the transformation of humic substances during composting, with fluorescence regions corresponding to tyrosine-like (I), tryptophan-like (II), fulvic-like (III), microbial byproducts (IV), and humic-like (V) substances (Fig. S4). Over time, fluorescence intensities in regions III and V increased significantly in T3, T4, and especially T5 ($P < 0.05$), indicating the accumulation of fulvic- and humic-like substances, which is consistent with the results of Liu et al. (2023). In contrast, region IV fluorescence declined, particularly in T5, reflecting rapid depletion of labile compounds. These trends are consistent with humification indices and suggest that biochar especially promotes the transformation and stabilization of humic substances.

To further characterize HS composition, PARAFAC analysis identified three distinct components (Fig. S5): C1 (protein-like, from microbial metabolism and labile organic matter degradation), C2 (UV- and visible-fulvic-like, from both high- and low-molecular-weight precursors), and C3 (humic-like, with complex aromatic and hydrophobic structures) (Fellman et al., 2010). Initially, C1 accounted for approximately 22.44

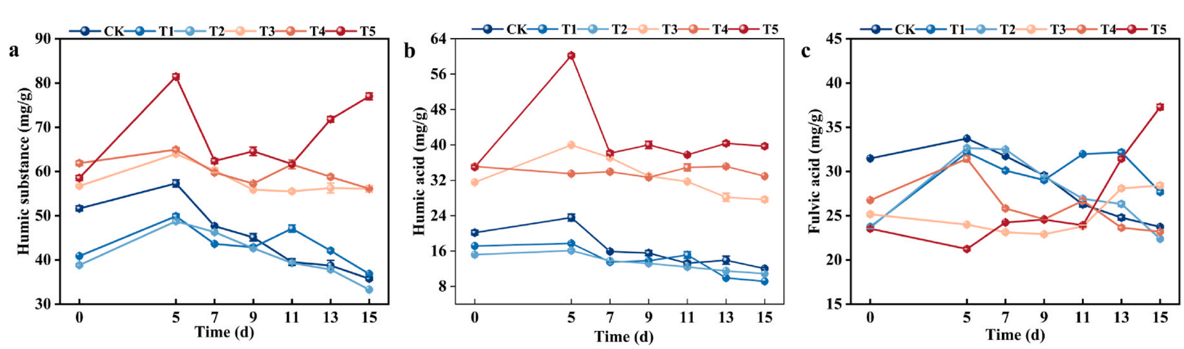

Fig. 3. Changes in humic acid components during composting: (a) Humus content; (b) Humic acid content; (c) Fulvic acid content.

%–24.96 % across treatments and increased during the thermophilic phase due to intensified microbial activity (Fig. 4). By the end of composting, C1 was significantly reduced in all biochar treatments compared to CK, indicating improved microbial conversion of proteinaceous substrates. C2 levels were consistently higher in biochar treatments than in CK, reaching 45.42 % in T5, likely due to the stabilization of intermediate fulvic compounds by biochar's aromatic structures. Although C3 declined overall due to mineralization, the smallest reduction occurred in T5 (4.83 %), which may be attributed to the higher humification efficiency and stabilization effects of BRB; its porous structure and abundant aromatic sites likely preserved and promoted the formation of stable, humic-like molecules during composting (Bo et al., 2023). At the end of composting, the combined proportion of C2+C3 in all BAC treatments was higher than that of CK, and the highest was T5 (69.61 %). The rise in C2 and preservation of C3 observed in T5 align well with the increases in HI and HR, reinforcing that BRB enhances the synthesis and stabilization of polymerized HS structures. These results confirm the role of biochar in enhancing compost humification and increasing HS structural complexity.

3.3. Effects of the application of biochar-amended compost products on soil and plants

3.3.1. Effects on soil properties

Application of BAC significantly improved the physicochemical properties of saline-alkali soils, with the regulatory effects varying depending on the humification degree and raw material characteristics. PMBC elevated soil pH by 2.92 %, which may be attributed to the leaching of Ca-Mg carbonate from the compost (Xu et al., 2017). However, other treatments reduced pH with concurrent EC increases (Fig. 5a–b). Although EC increased with higher BAC application rates, all values remained below the commonly recognized salinity threshold of 4 mS cm^{-1} for crop safety. The 8 % BRBC showed optimal saline-alkali buffering, achieving 2.4 % pH reduction and EC > 380 μs/cm via ionic-proton regulation mechanisms (Yuan et al., 2023). These improvements can be attributed to more mature humic substances present in highly humified BAC, which enhance cation exchange capacity and colloidal stability in the soil (Bian et al., 2024). Biochar can enhance C retention in organically-fertilized soils by forming organic-mineral associations through synergistic interactions between soil minerals and organic inputs (Plaza et al., 2016). The organic matter content significantly increased with BAC application rates (Fig. 5c), especially under PMBC (86.03 mg kg^{-1}), DGBC (84.73 mg kg^{-1}), and BRBC (77.15 mg kg^{-1}) treatments. This demonstrated that highly humified organic inputs effectively promote organic carbon accumulation and retention in soil systems.

Moreover, BAC markedly enhanced the availability of soil nutrients, with distinct advantages observed across different nutrient types. The 8 % PMBC application achieved peak alkali-hydrolyzed N (AN, 231.35 mg g^{-1}) and available P (AP, 39.65 mg kg^{-1}) concentrations (Fig. 5d–e),

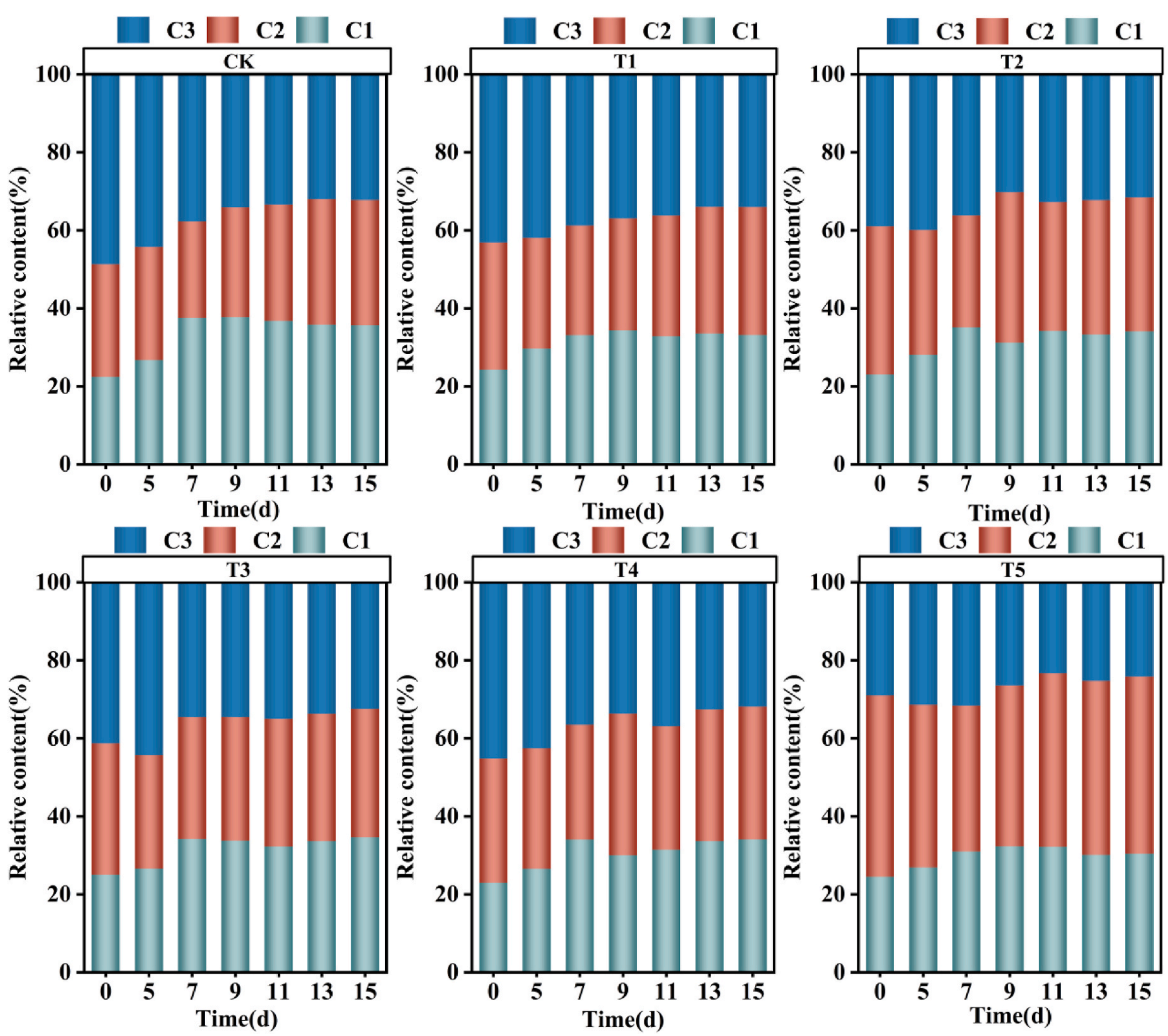

Fig. 4. Changes in the relative Fmax values of the three fluorescent components of humic substances (HS) under different BAC treatments.

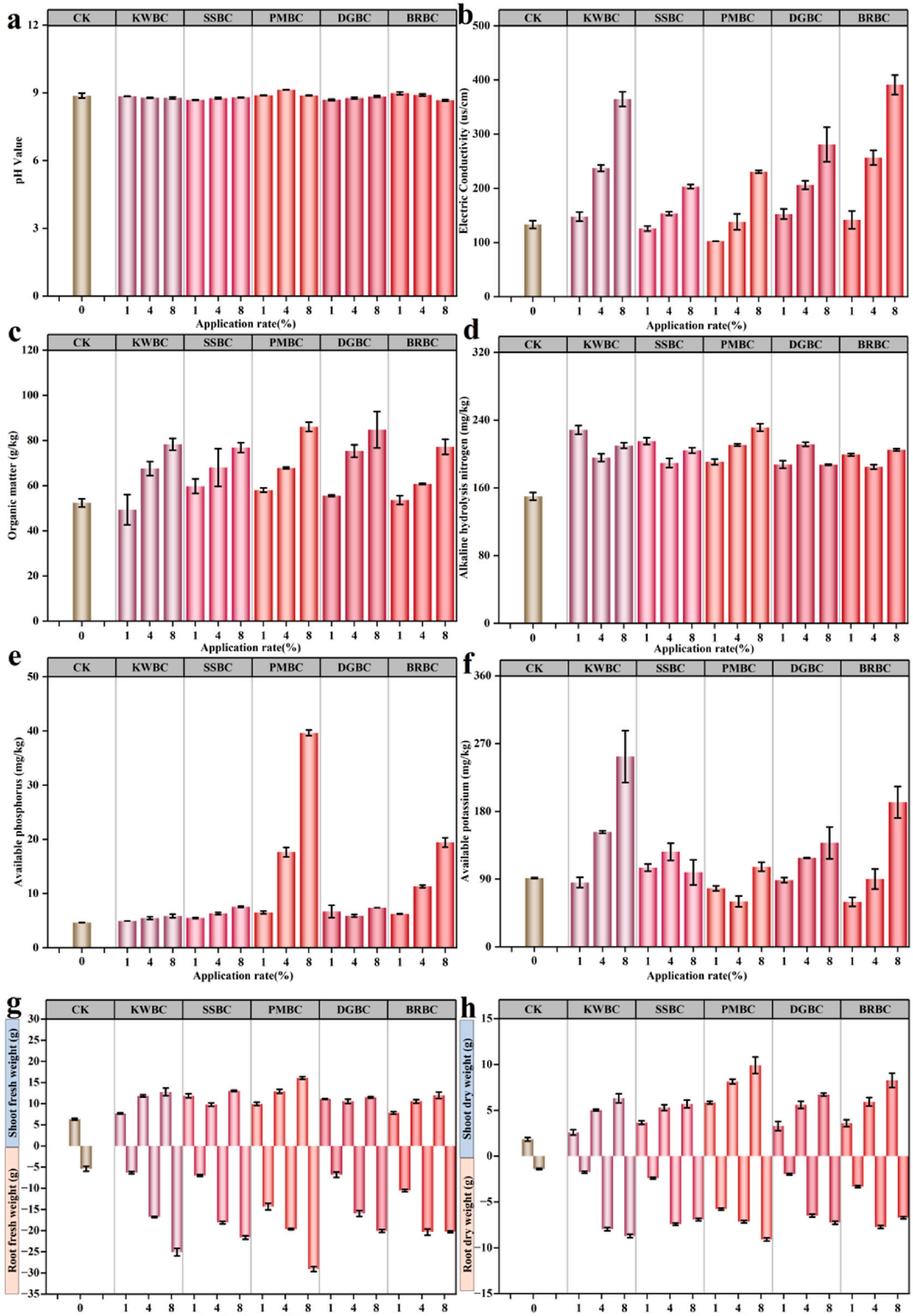

Fig. 5. Effects of different types and application rates of compost products on potting soil properties and plant growth: (a) pH, (b) Electrical conductivity, (c) Organic matter, (d) Alkali-hydrolyzed nitrogen, (e) Available phosphorus, (f) Available potassium, (g) Fresh biomass of shoots and roots, (h) Dry biomass of shoots and roots.

attributed to high N and P contents in manure biochar composts. Consistent with Goldan et al. (2023), manure compost elevates soil macronutrient bioavailability (N, P, K). BRBC showed slightly lower alkali-hydrolyzed N and available P contents compared to the PMBC, but provided relatively higher available potassium (AK, 204.98 mg kg^{-1}) (Fig. 5f), suggesting a more balanced nutrient profile. Although the KWBC yielded the highest AK (252.66 mg kg^{-1}), its lower degree of humification may limit its capacity for sustained soil fertility improvement. Overall, biochar-amended composts with higher humification levels not only act as nutrient sources but also controlled release and enhance soil nutrient retention (Luo et al., 2017), supporting their targeted use in saline-alkali soil remediation and fertility restoration.

Application of 8 % PMBC most effectively enhanced soil organic matter and retained available nitrogen and phosphorus, while 8 % BRBC exhibited superior performance in increasing available potassium and regulating soil pH and electrical conductivity. These findings suggested that the nutrient availability and pH regulation capabilities of BAC are closely linked to their humification degree and physicochemical characteristics.

3.3.2. Effects on plant growth

The application of BAC demonstrated significant positive effects on the performance of ryegrass under saline-alkali stress. Compared to the control (CK), where plants remained weak and stunted, all compost treatments markedly enhanced plant vigor, with taller shoots, broader leaves, and increased tillers observed after 60 days (Fig. S6). Higher BAC application rates generally enhanced growth improvements, particularly under PMBC and BRBC, suggesting a dose-dependent alleviation of saline-alkali growth restrictions.

Plant biomass serves as a sensitive indicator to evaluate the efficacy of different biochar-amended composts in ameliorating saline-alkali soils. The biomass, fresh weight, and dry weight increased as the proportion of fertilizer applied increased in treatments with BAC (Fig. 5g–h). At the application rate of ≤4 %, no significant differences in plant growth promotion were observed among the various biochar-amended composts. This may be attributed to the presence of abundant labile organic matter in BAC, which can attract degradative microorganisms even at low dosages (Han et al., 2024). The enhanced microbial activity in the rhizosphere likely stimulated root-associated microbial communities, thereby promoting plant growth (Li et al., 2022). A further comparison between root and shoot biomass revealed that the stimulatory effect was more pronounced in roots than in shoots. At the application rate of 8 %, the PMBC resulted in significantly higher biomass than all other treatments ($P < 0.05$), with shoot and root dry weights reaching 9.92 g and 9.09 g, respectively. This is likely due to the nutrient-rich and highly humified nature of BAC, which enhances microbial proliferation and subsequently facilitates plant growth, consistent with findings by Han et al. (2024). Similarly, BRBC and DGBC both characterized by relatively high degrees of humification, also promoted considerable biomass accumulation. In contrast, KWBC and SSBC exhibited relatively low biomass yields, likely due to their limited nutrient content and lower humification levels. Overall, PMBC proved most effective in promoting shoot and root development, and the optimal fertilization ratio was 8 %.

3.4. Influence mechanism of compost products on soil-plant systems

To further investigate the coupling mechanisms among biochar, compost properties (physicochemical and humification), soil properties (physicochemical and nutrient), and plant biomass, PLS-PM was employed to quantify their causal relationships under different application rates (Fig. 6). The model revealed that biochar exerted a positive effect on compost humification. Correlation analysis further showed that HS ($P < 0.05$) and FA ($P < 0.01$) were significantly positively correlated with the specific surface area of biochar (Fig. S7), indicating that the enhanced humification was likely attributed to the high surface area properties of biochar.

At a 1 % application rate, plant biomass was negatively correlated with biochar and soil properties, but positively correlated with compost properties and humification (Fig. 6a). The greatest total and direct effects on plant biomass were attributed to biochar (−0.782), soil physicochemical properties (−0.567), and soil nutrients (−0.576) (Fig. 6d). These negative coefficients indicate that low biochar application rates may disrupt nutrient balance or limit microbial activity from insufficient nutrients, while poor initial soil fertility further compromised biomass accumulation. Compost physicochemical properties and humification

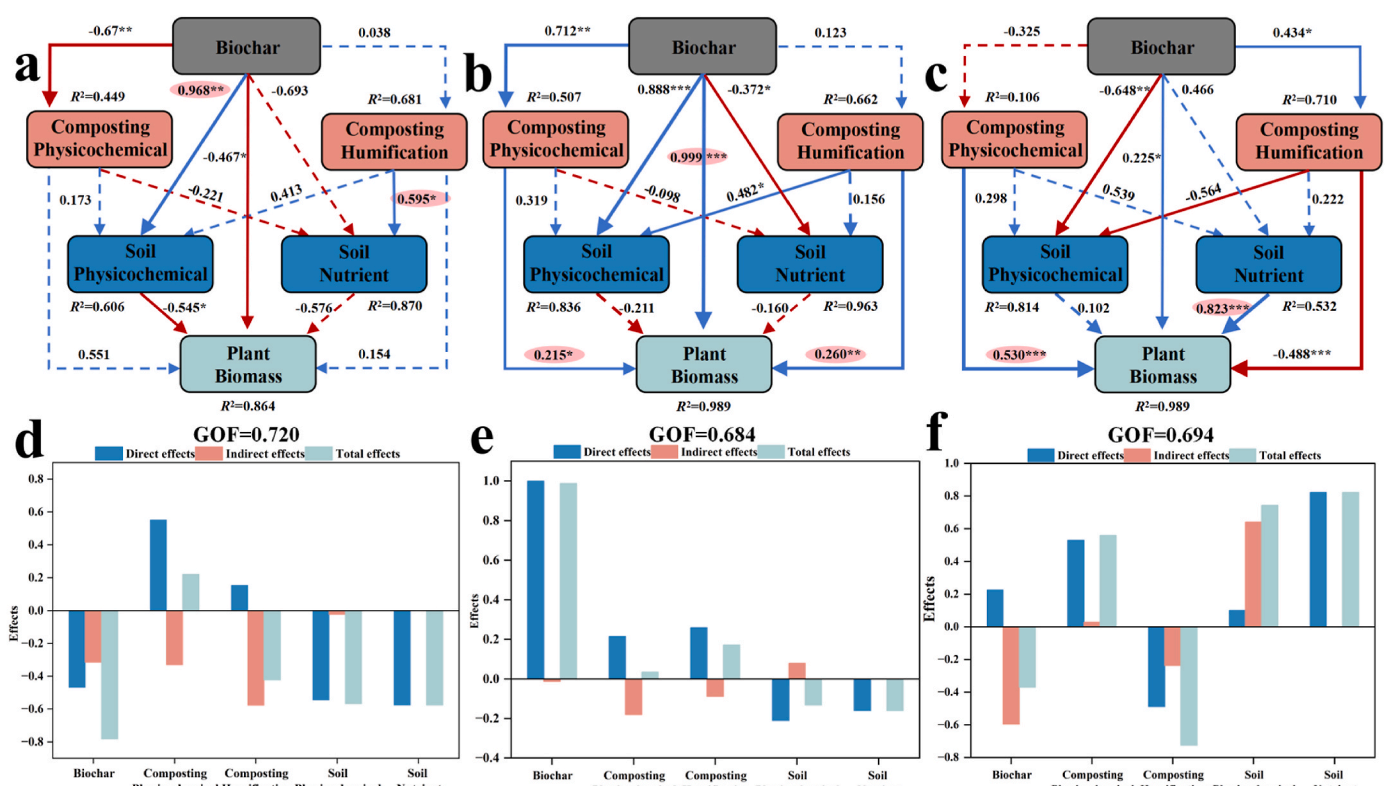

Fig. 6. PLS-PM analysis revealing direct and indirect effects of compost application rates on plant growth. (a–c) Pathways linking compost physicochemical properties, humification, soil physicochemical parameters, and nutrient availability to plant growth. Blue/red arrows denote positive/negative path coefficients. Goodness of Fit (GOF) indicates model validity. (d–f) Standardized direct, indirect, and total effects on plant biomass. (a, d: 1 % application rate; b, e: 4 % application rate; c, f: 8 % application rate; asterisks indicate significant correlations *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

exerted stronger indirect effects on plant biomass, mainly by enhancing soil properties and nutrient status, which subsequently affected plant growth. Correlation analysis revealed that soil pH was significantly positively correlated ($P < 0.05$) with biochar specific surface area, average pore diameter, compost pH, EC, HS, and FA, suggesting that BAC improves soil conditions primarily through pH regulation. This phenomenon was also supported by the findings of Adugna (2016), as well as the results shown in Fig. 5. Compared with the control, the growth of ryegrass was significantly enhanced under 1 % compost application (Fig. S6). Plant biomass was positively correlated with compost pH and HS ($P < 0.05$), but negatively correlated with soil pH, EC, AN, and AK ($P < 0.05$) (Fig. S7a). These results strongly suggest that a 1 % compost application can improve soil conditions and promote plant growth. However, its effectiveness is constrained by the application rate and unfavorable soil properties.

At the 4 % application rate, biochar showed a significant positive correlation with plant biomass (Fig. 6b), with the highest direct effect (0.805, $P < 0.01$) and total effect (1.109) (Fig. 6e). Correlation analysis further revealed that root biomass was significantly positively correlated with the specific surface area and average pore diameter of biochar, as well as with soil AP (Fig. S7b). A meta-analysis by Xiang et al. (2017) demonstrated that biochar enhances phosphorus uptake by promoting root elongation and branching, which may be attributed to its physicochemical properties such as high surface area, water retention capacity, and electrical conductivity. Compared with the 1 % application, the 4 % BAC treatment more effectively improved unfavorable soil properties, thereby weakening the negative effects of soil physicochemical properties and nutrients on plant biomass (Fig. 6e). In contrast, the direct positive effects of compost physicochemical properties and humification on plant biomass were enhanced, with standardized path coefficients of 0.215 ($P < 0.05$) and 0.260 ($P < 0.01$), respectively (Fig. 6e). This suggests that at moderate BAC doses, compost quality and degree of humification become the dominant drivers of plant growth, possibly by facilitating nutrient exchange and stimulating root metabolic activity. Positive correlations between compost pH and both soil pH/shoot biomass contrasted with AK's negative associations ($P < 0.05$; Fig. S7b), indicating compost pH regulates plant growth via potassium availability modulation. Elevated pH levels could enhance the exchangeable activity of Ca^{2+}/Mg^{2+}, which preferentially occupy soil colloidal sites, displacing K^{+} and promoting its leaching or uptake by plants (Rengel, 2002). Humic substance was significantly positively correlated with root biomass but negatively with soil AK ($P < 0.05$), potentially due to its ability to increase membrane permeability, enhance nutrient absorption, and directly stimulate root development (Guo et al., 2019). Overall, at the 4 % application rate, biochar-amended compost partially alleviated unfavorable soil conditions, with the biochar and humic substances in the compost directly stimulating plant root development.

At the 8 % application rate, plant biomass showed significant positive correlations with both biochar and soil nutrients (Fig. 6c), with standardized path coefficients of 0.225 and 0.823, respectively (Fig. 6f). The average pore size of biochar was positively correlated with soil AN, AP, and plant biomass ($P < 0.05$), possibly due to its ability to reduce nutrient leaching. Previous report has shown that biochar and biochar-compost mixtures can significantly decrease the leaching of N, P, K (Agegnehu et al., 2017). The physicochemical properties of compost also positively influenced soil properties and plant biomass (0.530, $P < 0.001$). Compost pH was significantly positively correlated with soil AN, AP, and plant biomass ($P < 0.05$), while compost EC was positively associated with soil EC and shoot biomass ($P < 0.01$). These findings suggest that compost pH and EC are key regulators linking soil nutrient dynamics and plant responses by modulating the availability of AN, AP, and AK (Han et al., 2024). Although compost humification showed relatively negative effects on plant biomass, it still positively influenced soil nutrients (0.222), similar to biochar. Humic acid content in compost was significantly positively correlated with plant shoot biomass ($P < 0.05$), indicating its potential role in promoting aboveground growth indirectly by improving soil properties or activating plant physiological responses. Structural equation modeling further showed that at the 8 % application rate, both soil physicochemical properties and nutrient status had direct and total positive effects on plant biomass, with the strongest effects observed for soil nutrients. The high path coefficient for soil nutrients (0.823) indicates that nutrient abundance is the primary limiting factor alleviated at higher BAC inputs, likely due to increased N, P, and K retention and reduced leaching. Collectively, these results demonstrate that applying 8 % BAC comprehensively alleviates unfavorable soil properties and indirectly promotes plant growth by enhancing nutrient availability.

4. Conclusions

This study demonstrated that the feedstock type of biomass-derived biochar significantly affected composting performance and humification efficiency. BRB and PMB, due to their superior surface area and porosity, prolonged the thermophilic phase and enhanced organic matter decomposition. Biochar positively influenced HS stabilization and humification, with PMB, DGB, and BRB showing the greatest effects. When applied to saline-alkali soil, BAC improved soil properties, nutrient availability, and plant growth, with an optimal application rate of 8 %. PLS-PM analysis revealed a dose-dependent response: moderate doses directly stimulated root growth via biochar and humic substances, while higher doses promoted growth mainly by improving soil nutrient status. These findings underscore the value of selecting appropriate biochar feedstocks to optimize compost quality and soil restoration strategies. However, future studies should benchmark against commercial organic fertilizers and conduct long-term field trials. Moreover, it is necessary to determine optimal application rates tailored to specific BAC types, soil characteristics, and crop species.

CRediT authorship contribution statement

Yuan Chang: Writing – original draft. **Yanting Chen:** Methodology, Conceptualization. **Yuquan Wei:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Nannan Miao:** Investigation, Formal analysis. **Zitong Kang:** Investigation, Data curation. **Yifan Zhang:** Visualization, Software. **Long D. Nghiem:** Investigation. **M.A.H. Johir:** Investigation. **Yanbin Guo:** Resources, Funding acquisition. **Yuhui Qiao:** Validation, Formal analysis. **Xiong Shi:** Validation, Resources, Formal analysis. **Ji Li:** Project administration, Funding acquisition, Conceptualization.

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.jenvman.2025.126667.

Data availability

Data will be made available on request.

References

Adugna, G., 2016. A review on impact of compost on soil properties, water use and crop productivity. Acad. Res. J. Agric. Sci. Res. 4 (3), 93–104. https://doi.org/10.14662/ARJASR2016.010.

Agegnehu, G., Srivastava, A.K., Bird, M.I., 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: a review. Appl. Soil Ecol. 119, 156–170. https://doi.org/10.1016/j.apsoil.2017.06.008.

Ahmad, M., Lee, S.S., Dou, X., Mohan, D., Sung, J.-K., Yang, J.E., Ok, Y.S., 2012. Effects of pyrolysis temperature on soybean stover-and peanut shell-derived biochar properties and TCE adsorption in water. Bioresour. Technol. 118, 536–544. https://doi.org/10.1016/j.biortech.2012.05.042.

Bian, H., Boguta, P., Huang, J., Deng, C., Kong, D., Zhou, H., Su, X., 2024. Transforming organic solid waste management: embracing humification for sustainable resource recovery. ACS Sustainable Resour. Manage. 1 (2), 181–198. https://doi.org/10.1021/acssusresmgt.3c00080.

Bo, X., Zhang, Z., Wang, J., Guo, S., Li, Z., Lin, H., Huang, Y., Han, Z., Kuzyakov, Y., Zou, J., 2023. Benefits and limitations of biochar for climate-smart agriculture: a review and case study from China. Biochar 5 (1), 77. https://doi.org/10.1007/s42773-023-00279-x.

Chang, Y., Zhou, K., Yang, T., Zhao, X., Li, R., Li, J., Xu, S., Feng, Z., Ding, X., Zhang, L., 2023. Bacillus licheniformis inoculation promoted humification process for kitchen waste composting: organic components transformation and bacterial metabolic mechanism. Environ. Res. 237, 117016. https://doi.org/10.1016/j.envres.2023.117016.

Chen, L., Chen, Y., Li, Y., Liu, Y., Jiang, H., Li, H., Yuan, Y., Chen, Y., Zou, B., 2023. Improving the humification by additives during composting: a review. Waste Manage 158, 93–106. https://doi.org/10.1016/j.wasman.2022.12.040.

Chen, W., Yang, Y., Chang, S., Wei, Y., Wu, Z., Tang, K., Chang, Y., Zhang, Y., Li, J., Xu, T., 2025. Changes of bacterial necromass and their roles in humus conversion during organic wastes composting from different sources. Bioresour. Technol. 416, 131740. https://doi.org/10.1016/j.biortech.2024.131740.

Chen, X., Du, Z., Liu, D., Wang, L., Pan, C., Wei, Z., Jia, L., Zhao, R., 2022. Biochar mitigates the biotoxicity of heavy metals in livestock manure during composting. Biochar 4 (1), 48. https://doi.org/10.1007/s42773-022-00174-x.

Chi, W., Nan, Q., Liu, Y., Dong, D., Qin, Y., Li, S., Wu, W., 2024. Stress resistance enhancing with biochar application and promotion on crop growth. Biochar 6 (1), 43. https://doi.org/10.1007/s42773-024-00336-z.

Dahlawi, S., Naeem, A., Rengel, Z., Naidu, R., 2018. Biochar application for the remediation of salt-affected soils: challenges and opportunities. Sci. Total Environ. 625, 320–335. https://doi.org/10.1016/j.scitotenv.2017.12.257.

Fellman, J.B., Hood, E., Spencer, R.G., 2010. Fluorescence spectroscopy opens new windows into dissolved organic matter dynamics in freshwater ecosystems: a review. Limnol. Oceanogr. 55 (6), 2452–2462. https://doi.org/10.4319/lo.2010.55.6.2452.

Gao, X., Xu, Z., Li, Y., Zhang, L., Li, G., Nghiem, L.D., Luo, W., 2021. Bacterial dynamics for gaseous emission and humification in bio-augmented composting of kitchen waste. Sci. Total Environ. 801, 149640. https://doi.org/10.1016/j.scitotenv.2021.149640.

Godlewska, P., Schmidt, H.P., Ok, Y.S., Oleszczuk, P., 2017. Biochar for composting improvement and contaminants reduction. A review. Bioresour. Technol. 246, 193–202. https://doi.org/10.1016/j.biortech.2017.07.095.

Goldan, E., Nedeff, V., Barsan, N., Culea, M., Panainte-Lehadus, M., Mosnegutu, E., Tomozei, C., Chitimus, D., Irimia, O., 2023. Assessment of manure compost used as soil amendment—A review. Processes 11 (4), 1167. https://doi.org/10.3390/pr11041167.

Guo, X., Liu, H., Wu, S., 2019. Humic substances developed during organic waste composting: formation mechanisms, structural properties, and agronomic functions. Sci. Total Environ. 662, 501–510. https://doi.org/10.1016/j.scitotenv.2019.01.137.

Han, L., Li, L., Xu, X., Ye, W., Zhang, F., Xu, Y., Peng, X., Zhen, F., 2024. Utilization of short-term high temperature pretreatment for food waste composting: effects of end-products on soil properties and plant growth. J. Clean. Prod. 438, 140790. https://doi.org/10.1016/j.jclepro.2024.140790.

He, W., Rong, S., Wang, J., Zhao, Y., Liang, Y., Huang, J., Meng, L., Feng, Y., Xue, L., 2024. Different crystalline manganese dioxide and biochar co-conditioning aerobic composting: reduced ammonia volatilization and improved organic fertilizer quality. J. Hazard. Mater. 465, 133127. https://doi.org/10.1016/j.jhazmat.2023.133127.

He, X., Han, L., Huang, G., 2020. Analysis of regulative variables on greenhouse gas emissions and spatial pore gas concentrations with modeling during large-scale trough composting. J. Clean. Prod. 277, 124066. https://doi.org/10.1016/j.jclepro.2020.124066.

He, X., Yin, H., Han, L., Cui, R., Fang, C., Huang, G., 2019. Effects of biochar size and type on gaseous emissions during pig manure/wheat straw aerobic composting: insights into multivariate-microscale characterization and microbial mechanism. Bioresour. Technol. 271, 375–382.

Ippolito, J.A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J.M., Fuertes-Mendizabal, T., Cayuela, M.L., Sigua, G., Novak, J., Spokas, K., 2020. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar 2, 421–438.

Kołodyńska, D., Krukowska, J., Thomas, P., 2017. Comparison of sorption and desorption studies of heavy metal ions from biochar and commercial active carbon. Chem. Eng. J. 307, 353–363. https://doi.org/10.1016/j.cej.2016.08.088.

Kong, Y., Zhang, J., Zhang, X., Gao, X., Yin, J., Wang, G., Li, J., Li, G., Cui, Z., Yuan, J., 2024. Applicability and limitation of compost maturity evaluation indicators: a review. Chem. Eng. J. 489, 151386. https://doi.org/10.1016/j.cej.2024.151386.

Li, J., Zhang, L., Yao, G., Zhu, L., Lin, J., Wang, C., Du, B., Ding, Y., Mei, X., 2022. Synergistic effect of co-culture rhizosphere streptomyces: a promising strategy to enhance antimicrobial activity and plant growth-promoting function. Front. Microbiol. 13, 976484. https://doi.org/10.3389/fmicb.2022.976484.

Li, M., Jiang, H., Li, R., Liu, W., Xie, Y., Wu, W., Liu, D., Wu, M., Qiu, Z., 2024. Effects of biochar-loaded microbial agent in regulating nitrogen transformation and integration into humification for straw composting. Bioresour. Technol. 417, 131873. https://doi.org/10.1016/j.biortech.2024.131873.

Liang, J.F., Li, Q.W., Gao, J.Q., Feng, J.G., Zhang, X.Y., Hao, Y.J., Yu, F.H., 2021. Biochar-compost addition benefits Phragmites australis growth and soil property in coastal wetlands. Sci. Total Environ. 769, 145166. https://doi.org/10.1016/j.scitotenv.2021.145166.

Liang, X., Wen, X., Yang, H., Lu, H., Wang, A., Liu, S., Li, Q., 2024. Incorporating microbial inoculants to reduce nitrogen loss during sludge composting by suppressing denitrification and promoting ammonia assimilation. Sci. Total Environ. 915, 170000. https://doi.org/10.1016/j.scitotenv.2024.170000.

Liu, Q., He, X., Wang, K., Li, D., 2023. Biochar drives humus formation during composting by regulating the specialized metabolic features of microbiome. Chem. Eng. J. 458, 141380. https://doi.org/10.1016/j.cej.2023.141380.

Luo, X., Liu, G., Xia, Y., Chen, L., Jiang, Z., Zheng, H., Wang, Z., 2017. Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. J. Soils Sediments 17, 780–789. https://doi.org/10.1007/s11368-016-1361-1.

Mabrouk, O., Hamdi, H., Sayadi, S., Al-Ghouti, M.A., Abu-Dieyeh, M.H., Zouari, N., 2023. Reuse of sludge as organic soil amendment: insights into the current situation and potential challenges. Sustainability 15 (8), 6773. https://doi.org/10.3390/su15086773.

Murphy, K.R., Stedmon, C.A., Graeber, D., Bro, R., 2013. Fluorescence spectroscopy and multi-way techniques. PARAFAC. Anal. Methods. 5 (23), 6557–6566. https://doi.org/10.1039/C3AY41160E.

Nidheesh, P., Gopinath, A., Ranjith, N., Akre, A.P., Sreedharan, V., Kumar, M.S., 2021. Potential role of biochar in advanced oxidation processes: a sustainable approach. Chem. Eng. J. 405, 126582. https://doi.org/10.1016/j.cej.2020.126582.

Plaza, C., Giannetta, B., Fernández, J.M., López-de-Sá, E.G., Polo, A., Gascó, G., Méndez, A., Zaccone, C., 2016. Response of different soil organic matter pools to biochar and organic fertilizers. Agric. Ecosyst. Environ. 225, 150–159. https://doi.org/10.1016/j.agee.2016.04.014.

Pottipati, S., Ashmita, K., S, K.A., 2021. Process optimization by combining in-vessel composting and vermicomposting of vegetable waste. Bioresour. Technol. 346, 126357. https://doi.org/10.1016/J.BIORTECH.2021.126357, 126357.

Qi, H., Gao, W., Xie, L., Zhang, G., Song, C., Wei, Z., Hu, N., Li, T., 2024. Effect of MnO_2-biochar composites on promoting humification during chicken manure composting. Biochar 6 (1), 32. https://doi.org/10.1007/S42773-024-00315-4.

Qian, S., Zhou, X., Fu, Y., Song, B., Yan, H., Chen, Z., Sun, Q., Ye, H., Qin, L., Lai, C., 2023. Biochar-compost as a new option for soil improvement: application in various problem soils. Sci. Total Environ. 870, 162024. https://doi.org/10.1016/J.SCITOTENV.2023.162024.

Rengel, Z., 2002. Role of pH in availability of ions in soil. In: Handbook of Plant Growth Ph as the Master Variable. CRC Press, pp. 317–342. https://doi.org/10.1201/9780203910344.

Shen, B., Zhang, X., Zhao, Y., Tao, W., Wei, Z., Song, C., 2024. Investigating the effect of Fenton-like pretreatment-clay mineral addition on humic substance during straw composting. Chem. Eng. J. 496, 154199. https://doi.org/10.1016/j.cej.2024.154199.

Wang, C., Tu, Q., Dong, D., Strong, P., Wang, H., Sun, B., Wu, W., 2014. Spectroscopic evidence for biochar amendment promoting humic acid synthesis and intensifying humification during composting. J. Hazard. Mater. 280, 409–416. https://doi.org/10.1016/j.jhazmat.2014.08.030.

Wang, F., Zhou, F., Zhang, L., Liu, W., Su, Y., Zhang, Y., Hong, S., Zhan, M., Xie, B., Zhou, Y., 2025. Mechanisms of manganese-modified biochar and white-rot fungi in enhancing compost humification: boosting polyphenol pathway by lignocellulose degradation. Chem. Eng. J. 507, 160637. https://doi.org/10.1016/j.cej.2025.160637.

Waqas, M., Nizami, A., Aburiazaiza, A., Barakat, M., Ismail, I., Rashid, M., 2018. Optimization of food waste compost with the use of biochar. J. Environ. Manag. 216, 70–81. https://doi.org/10.1016/j.jenvman.2017.06.015.

Wu, X., Zhao, X., Wu, W., Hou, J., Zhang, W., Tang, D.K.H., Zhang, X., Yang, G., Zhang, Z., Yao, Y., 2024. Biotic and abiotic effects of manganese salt and apple branch biochar co-application on humification in the co-composting of hog manure and sawdust. Chem. Eng. J. 482, 149077. https://doi.org/10.1016/j.cej.2024.149077.

Xiang, Y., Deng, Q., Duan, H., Guo, Y., 2017. Effects of biochar application on root traits: a meta-analysis. GCB Bioenergy 9 (10), 1563–1572. https://doi.org/10.1111/gcbb.12449.

Xu, X., Zhao, Y., Sima, J., Zhao, L., Mašek, O., Cao, X., 2017. Indispensable role of biochar-inherent mineral constituents in its environmental applications: a review. Bioresour. Technol. 241, 887–899. https://doi.org/10.1016/j.biortech.2017.06.023.

Yuan, Y., Liu, Q., Zheng, H., Li, M., Liu, Y., Wang, X., Peng, Y., Luo, X., Li, F., Li, X., 2023. Biochar as a sustainable tool for improving the health of salt-affected soils. Soil Environ. Health 1 (3), 100033. https://doi.org/10.1016/j.seh.2023.100033.

Yui, L., Mukesh, K.A., Raveendran, S., Parameswaran, B., Zengqiang, Z., J, T.M., 2023. Biochar preparation and evaluation of its effect in composting mechanism: a review. Bioresour. Technol. 384, 129329. https://doi.org/10.1016/j.biortech.2023.129329, 129329.

Zhan, Y., Chang, S., Chen, Y., Chang, Y., Chen, P., Chen, Y., Zhang, L., Yang, L., Xia, X., Li, J., 2024. Effect of auxiliary materials on the formation of humic acid carbon and nitrogen and bacterial dynamics in kitchen waste composting. J. Environ. Chem. Eng. 12 (4), 113190. https://doi.org/10.1016/j.jece.2024.113190.

Zhang, Z., Zhao, Y., Wang, R., Lu, Q., Wu, J., Zhang, D., Nie, Z., Wei, Z., 2018. Effect of the addition of exogenous precursors on humic substance formation during composting. Waste Manage 79, 462–471. https://doi.org/10.1016/j.wasman.2018.08.025.

Zhou, G., Xu, X., Qiu, X., Zhang, J., 2019. Biochar influences the succession of microbial communities and the metabolic functions during rice straw composting with pig manure. Bioresour. Technol. 272, 10–18. https://doi.org/10.1016/j.biortech.2018.09.135.

Zhou, S., Jiang, Z., Shen, J., Yao, Q., Yang, X., Li, X., Awasthi, M.K., Zhang, Z., 2023. Biochar-amended compost as a promising soil amendment for enhancing plant productivity: a meta-analysis study. Sci. Total Environ. 879, 163067. https://doi.org/10.1016/j.scitotenv.2023.163067.