

Article

Effects of Polymer-Based Soil Conditioner and Humic Acid on Soil Properties and Cotton Yield in Saline–Sodic Soils

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Abstract

Secondary salinization in mulched drip-irrigated cotton fields of arid oasis–desert transition zones in Xinjiang imposes coupled root-zone constraints, including salt-induced aggregate structural degradation and ionic stress. However, field evidence remains limited on whether integrating a structure-oriented soil conditioner with humic acid can generate stable improvements across growing seasons. A two-year field experiment with a randomized block design (three replicates) was conducted to evaluate four treatments: control (CK), polyacrylamide (PAM, 30 kg ha^{−1}), humic acid (HA, 450 kg ha^{−1}), and PAM + HA. Soil physical and chemical properties and aggregate-size distribution were determined after harvest, while enzyme activities and root traits were assessed at the flowering–boll stage. Structural equation modeling (SEM) and random forest (RF) analysis were used to explore soil–root–yield linkages and identify key soil predictors associated with yield variation. Treatment effects were most evident in the 0–20 cm layer, with PAM + HA showing the greatest overall improvement. In the topsoil, PAM + HA lowered soil pH from 8.35 to 7.88 in 2024 ($p < 0.05$), increased soil organic carbon (SOC) to 4.29 g kg^{−1} in 2025 ($p < 0.01$), and increased NO₃[−]–N to 25.51 and 30.27 mg kg^{−1} in 2024 and 2025, respectively (both $p < 0.05$). PAM + HA also enhanced cellulase activity from 6.17 to 16.85 mg glucose g^{−1} 72 h^{−1} in 2024 and increased seed cotton yield to 6683.69 and 5996.89 kg ha^{−1} in 2024 and 2025, with a 51.0% yield increase over CK in 2024. SEM showed that root development had the strongest direct positive effect on yield ($\beta = 0.79$, $R^2 = 0.63$; goodness of fit (GOF) = 0.74), while random forest identified alkaline phosphatase, cellulase, and NO₃[−]–N as the main yield predictors (out-of-bag R^2 (OOB R^2) = 0.672, $p = 0.01$). This study elucidated the effects of the combined application of a structure-oriented soil conditioner and humic acid on the root-zone environment of mulched drip-irrigated cotton fields in arid regions, providing a theoretical basis for the coordinated regulation of soil structural improvement and nutrient activation in saline–sodic cotton fields.

Keywords: saline–sodic soil; mulched drip irrigation; humic acid; soil conditioner; structural equation modeling



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1. Introduction

Cotton production in the arid irrigated regions of Xinjiang is increasingly constrained by soil salinity and sodicity under a climate of low precipitation and high evaporative demand, which together threaten yield stability [1]. Under strong evapotranspiration, dissolved salts migrate upward with capillary water flow and tend to accumulate in the cultivated layer, particularly under mulched drip irrigation systems characterized by frequent wetting–drying cycles [2,3]. This process promotes secondary salinization in the plough layer, leading to progressive salt accumulation in the root-active zone and increased risks of yield fluctuation. Importantly, the consequence is not merely salt accumulation itself, but the progressive degradation of the root-zone environment, which reduces resource-use efficiency and constrains cotton productivity under long-term mulched drip irrigation [1].

In saline–sodic soils, salt accumulation induces a set of interacting physical, chemical, and biological constraints that collectively deteriorate the root-zone environment. From a physical perspective, excessive exchangeable Na^+ can displace Ca^{2+} from soil colloids, weakening inter-particle bonding and destabilizing soil aggregates [4]. The breakdown of macro-aggregates weakens structural stability, leading to compaction, restricted infiltration, and limited gas exchange. Such structural degradation increases mechanical impedance and hypoxia risk, thereby constraining root penetration and activity [5,6]. Chemically, elevated concentrations of Na^+ and Cl^- intensify ionic stress, disrupt nutrient uptake through competitive interactions, and reduce the availability of essential nutrients [7,8]. High soil pH often accompanies sodicity, further influencing nutrient solubility, fixation processes, and overall nutrient availability. These ionic imbalances increase the physiological cost of water and nutrient acquisition, ultimately suppressing root growth and metabolic activity. Biologically, saline stress can inhibit microbial activity and reduce enzyme-mediated nutrient transformation processes in the rhizosphere [9,10]. Reduced activities of key enzymes involved in carbon, nitrogen, and phosphorus cycling further limit nutrient turnover and availability in the root-active layer. Together, these physical, chemical, and biological constraints converge in the cultivated layer, impairing root development and compromising cotton productivity.

To mitigate root-zone degradation caused by secondary salinization, soil amendments have been increasingly adopted as a practical strategy to restore soil function in saline–sodic systems. Among the available options, structure-oriented conditioners and organic amendments represent two complementary remediation pathways. Polyacrylamide (PAM) is a water-soluble synthetic polymer widely used as a soil conditioner because it can adsorb onto mineral surfaces and bind soil particles, thereby promoting flocculation, aggregate stabilization, and pore continuity in salt-affected soils. Previous studies have shown that PAM can improve aggregate stability, infiltration, and structural resistance to dispersion, although attention should also be paid to its environmental fate and the potential risks associated with acrylamide residues or degradation products [11,12]. In contrast, humic acid (HA) mainly contributes to soil organic carbon accumulation, buffering capacity, nutrient retention, and biologically mediated nutrient transformations [9,10]. Compared with gypsum, which is mainly used to replace exchangeable Na^+ , or biochar, which often emphasizes carbon sequestration and longer-term structural benefits [13,14], PAM and HA were selected here because they more directly target the coupled structural and fertility-related constraints of the root zone under drip-irrigated saline–sodic cotton systems. Therefore, integrating a structure-oriented conditioner with an organic amendment may provide a balanced strategy to address both structural and fertility-related constraints in saline–sodic soils [15].

Although previous studies have examined PAM or HA individually in salt-affected soils, important gaps remain in understanding their joint roles in saline–sodic cotton fields.

Field evidence for the combined effects of PAM and HA remains limited, particularly under mulched drip irrigation, where salt redistribution and root-zone processes are highly dynamic. Moreover, most existing studies have mainly reported parallel changes in soil properties and crop performance, whereas the pathways linking soil physical, chemical, and biological changes to root development and yield formation remain poorly resolved. The key soil variables most strongly associated with yield variation are also still unclear. Therefore, the novelty of the present study lies not only in evaluating the combined effects of a structure-oriented conditioner and humic acid under field conditions, but also in integrating structural equation modeling (SEM) and random forest (RF) analysis as complementary tools: SEM was used to evaluate direct and indirect soil–root–yield linkages, whereas RF was used to identify and rank the soil variables most strongly associated with yield variation.

Given these challenges, evaluating amendment strategies for saline–sodic cotton soils under mulched drip irrigation calls for an approach that considers soil structure, fertility status, biological processes, and crop responses within the same field context. Here, we combined a two-year field experiment with an analytical framework that integrates depth-resolved measurements of soil physical and chemical properties, enzyme activities, root traits, and yield components. Accordingly, the objectives of this study were: (1) to quantify the effects of a structure-oriented soil conditioner and humic acid, applied alone and in combination, on soil structure, pH and fertility-related pools, enzyme activities, root traits, and cotton yield formation across two growing seasons; (2) to evaluate the soil–root–yield relationships using SEM; and (3) to identify soil variables most strongly associated with yield variation using random forest analysis.

2. Materials and Methods

2.1. Site Description

The field study was conducted in the saline soil improvement demonstration area at Jiashi General Farm, located within the Third Division of Xinjiang Production and Construction Corps (39°40' N, 77°48' E), China (Figure 1). The region experiences a cold desert climate, classified as BWk under the Köppen–Geiger system, with an average annual temperature of 11.7 °C. Precipitation in the area totals 54 mm annually, while evaporation is much higher at 2251.1 mm. For the cotton growing seasons in 2024 and 2025, the mean temperatures were 23 °C and 25.6 °C, respectively, with precipitation measuring 22 mm and 26 mm. In 2022, the soil characteristics at the 0–40 cm depth were as follows: gray desert soil with a bulk density of 1.40 g cm^{−3}, field water capacity of 0.21 m³ m^{−3}, soil organic carbon at 12.69 g kg^{−1}, alkali-hydrolyzable nitrogen of 23.05 mg kg^{−1}, available phosphorus at 10.47 mg kg^{−1}, exchangeable potassium of 173.55 mg kg^{−1}, electrical conductivity (EC) of 3.41 dS m^{−1}, and a pH of 7.80. The water table in this area fluctuates between 5 and 8 m, with groundwater mineralization levels ranging from 10.44 to 19.58 g L^{−1}. Before treatment establishment, the field was leveled and managed uniformly, and the experimental area was selected from a relatively homogeneous part of the demonstration field to reduce background heterogeneity in soil conditions.

2.2. Field Experiments

This study involved four treatments applied prior to cotton sowing: a control treatment (no conditioner, CK), polyacrylamide (PAM, 30 kg ha^{−1}), humic acid (HA, 450 kg ha^{−1}), and a combination of PAM and HA at the same application rates. The experiment was conducted using a randomized block design with three replications. Each subplot had an area of 6.75 × 20 m², with rows spaced 205 cm apart. Before treatment establishment, no PAM or humic acid had been applied to the experimental field. Polyacrylamide and

humic acid were supplied by Xinjiang Shuanglong Humic Acid Co., Ltd., Urumqi, China. The application rates of PAM (30 kg ha^{-1}) and HA (450 kg ha^{-1}) were selected according to the manufacturer's recommendations. The PAM product, used as a structure-oriented soil conditioner, contained $>90\%$ active ingredient and had a degree of hydrolysis of 30% , while the humic acid content (dry basis) was $\geq 60\%$. Both amendments were incorporated into the soil as a one-time application before sowing. These treatments were designed to compare the individual and combined effects of a structure-oriented conditioner (PAM) and an organic amendment (HA) under identical field conditions. Except for amendment treatments, all plots were managed identically in terms of cotton cultivar, planting density, irrigation, fertilization, mulching, and other field operations throughout the study period.

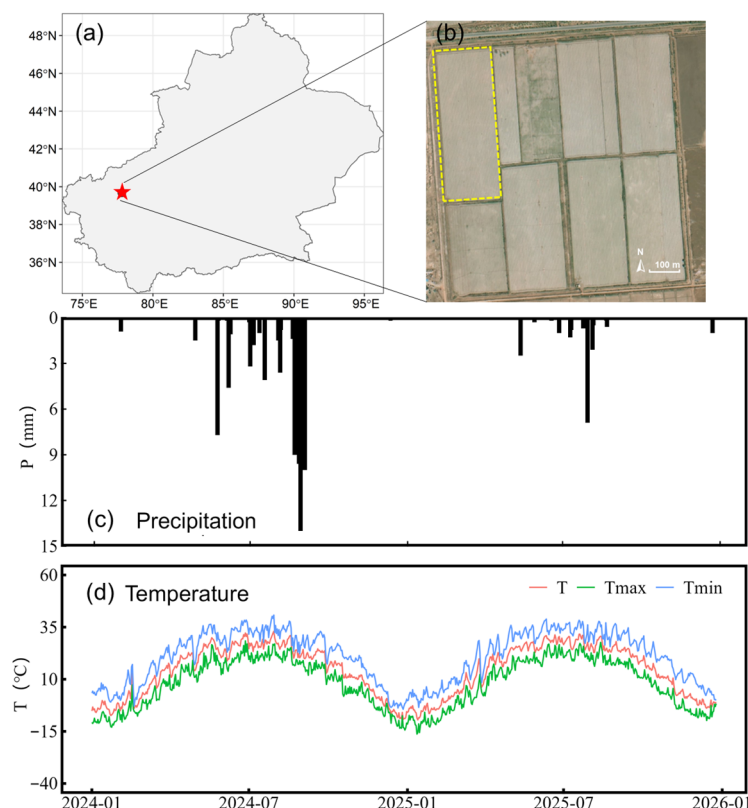


Figure 1. Geographic location and climatic conditions at the study site. Panel (a,b) show the geographic location of the study site in Xinjiang, China, with detailed maps of the region, highlighting the location of the experimental site. Panel (c) presents the monthly precipitation (mm) recorded at the site from 2024 to 2025. Panel (d) displays the temperature variations ($^{\circ}\text{C}$), including the monthly average temperature (T), maximum temperature (Tmax), and minimum temperature (Tmin) during the same period.

Cotton cultivar Xinluzhong 67 was planted on 20 April 2024, with harvest dates scheduled for 5 October 2024, and for the second planting, sowing occurred on 25 April 2025, with harvesting set for 10 October 2025. The cotton was planted in six rows, arranged under a 2.05 m wide strip of high-density polyethylene film, with row intervals of 0.10 m, 0.66 m, 0.10 m, 0.66 m, and 0.10 m. Between the narrow rows, drip irrigation tape was installed, featuring emitters spaced 20 cm apart and a flow rate of 2.6 L h^{-1} . Each row had a seed spacing of 10 cm, resulting in an estimated plant density of approximately 220,000 plants per hectare.

Detailed irrigation and fertilization schedules are provided in Table 1. For the 2024 and 2025 growing seasons, the total irrigation volume was 815 mm. Fertilizer applications consisted of 300 kg N ha^{-1} (urea, 46% N), $120 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ (calcium superphosphate,

46% P_2O_5), and 60 kg K_2O ha⁻¹ (potassium sulfate, 52% K_2O). Before sowing, 20% of the urea was applied in bands along the rows, while the remaining 80% was dissolved and distributed through six fertigation events throughout the growing season. All phosphorus and potassium fertilizers were evenly mixed into the soil using a rotavator prior to planting.

Table 1. Irrigation schedule of cotton in irrigation seasons.

Irrigation Time	April	May	June	July	August	Total
Irrigation amounts/mm	135	50	195	280	155	815

2.3. Sampling and Analysis

Soil sampling was conducted at the flowering–boll stage from three sampling points arranged diagonally within each plot, as this stage is critical for integrated evaluation of soil conditions, root traits, and yield-related responses in cotton. Using a soil auger, samples were collected from depths of 0–20 cm and 20–40 cm, immediately placed in sealed plastic bags, transported to the laboratory, and processed according to subsequent analytical requirements. On the same day, undisturbed soil cores for bulk density and aggregate analysis were also obtained. This involved excavating a soil profile pit measuring 100 cm × 100 cm × 80 cm (L × W × D) at each sampling area. Undisturbed samples were collected from the 0–20 cm and 20–40 cm layers of the pit’s vertical face. The 0–20 cm layer was sampled using a cutting ring (100 cm³), while a small shovel was used for the 20–40 cm layer. These samples were then carefully transported to the laboratory in rigid plastic boxes. All samples were air-dried in a shaded location after removing stones, plant residues, and plastic film debris. Next, the samples were carefully separated along natural structural planes into small clods of about 1 cm³, homogenized, and then sieved through a 2 mm mesh to prepare them for further analysis.

2.3.1. Determination of Soil Physical Properties

Soil bulk density was measured using the ring knife method. Soil moisture content was determined gravimetrically by oven-drying the samples at 105 °C for 48 h. The size distribution of water-stable aggregates was assessed through wet sieve analysis, which categorized macroaggregates as those larger than 0.25 mm, and microaggregates as those between 0.053 and 0.25 mm.

$$SBD = (W2 - W3)/V \quad (1)$$

$$SP = (1 - SBD/PD) \times 100\% \quad (2)$$

$$SMC = (W1 - W2)/(W2 - W3) \quad (3)$$

SBD represents the soil bulk density in g·cm⁻³, SP indicates soil porosity as a percentage (%), and SMC reflects the soil moisture content, also in percentage (%). The undisturbed soil samples were carefully transported to the laboratory, where their fresh weight (W1) was measured. After drying in an oven at 105 °C to a constant weight, the samples were reweighed (W2) to calculate the bulk density. The volume of the ring cutter was denoted as V (in cm³), and its weight was recorded as W3. The particle density (PD) of the soil was considered to be 2.65 g·cm⁻³. The wet sieve analysis determined the mass percentage of macroaggregates and microaggregates. The formulas used are as follows:

$$w_i = W_i/50 \times 100\% \quad (4)$$

$$MAG = (W_i > 0.25)/50 \times 100\% \quad (5)$$

$$MIG = (W_i < 0.25)/50 \times 100\% \quad (6)$$

MAG refers to the mass percentage of macroaggregates (larger than 0.25 mm), while MIG represents the mass percentage of microaggregates (ranging from 0.053 to 0.25 mm). The variable w_i denotes the mass percentage (%) of the i th aggregate level, x_i is the aggregate diameter at a specific particle size, and W_i represents the dry mass of aggregates at that particular size.

2.3.2. Determination of Soil Chemical Properties

Soil pH was determined with a pH meter (S-400, Mettler Toledo, Greifensee, Switzerland) using the potentiometric method. For preparation, 10 g of air-dried soil (sieved to 0.15 mm) was mixed with 25 mL of ultrapure water in a 50 mL beaker. The mixture was agitated for 30 min and then allowed to settle before measuring the pH [16].

Soil organic carbon content was determined [17] as follows: a 100 mg sample of air-dried soil (sieved to 0.1 mm) was wrapped in silver foil and treated with several drops of $2 \text{ mol} \cdot \text{L}^{-1}$ HCl for over an hour to remove inorganic carbonates. The sample was then dried in an oven at 50°C until a constant weight was reached. If effervescence was observed during heating, another drop of HCl was added, and the acidification process was repeated. The decarbonated sample was analyzed for Total Carbon, representing soil organic carbon, using a CN-802 analyzer (VELP, Monza, Italy) with non-dispersive infrared detection. For the determination of ammonium (NH_4^+-N) and nitrate (NO_3^--N), fresh soil samples (sieved to 2 mm) were extracted with a 1 M KCl solution. The concentrations of these nutrients in the extracts were measured using an auto discrete analyzer (Cleverchem 380, DeChem-Tech, Hamburg, Germany) [18].

2.3.3. Determination of Enzyme Activities

Amylase activity was determined using the 3,5-dinitrosalicylic acid (DNS) colorimetric method following Tabatabai (1994) [19]. Briefly, 5 g of fresh soil was mixed with toluene to inhibit microbial growth during incubation, followed by the addition of soluble starch solution and phosphate buffer (pH 6.8). The mixture was incubated at 37°C for 24 h under controlled conditions. After incubation, the suspension was filtered, and 1 mL of the filtrate was reacted with 3 mL of DNS reagent in a boiling water bath for 5 min to allow color development. After cooling to room temperature, the reaction mixture was diluted to 25 mL with distilled water, and absorbance was measured at 508 nm using a spectrophotometer (UV-1800, Mapada, Shanghai, China). Amylase activity was calculated from a glucose standard curve and expressed as $\text{mg glucose g}^{-1} 24 \text{ h}^{-1}$.

Cellulase activity was measured using carboxymethyl cellulose (CMC) as the substrate and quantified via the DNS colorimetric method [20]. Ten grams of fresh soil was pretreated with 1.5 mL of toluene, after which CMC solution and acetate buffer (pH 5.5) were added. The mixture was incubated at 37°C for 72 h to allow enzymatic hydrolysis of cellulose derivatives. Following incubation, the suspension was filtered, and the reducing sugars released into the filtrate were quantified spectrophotometrically at 540 nm after reaction with DNS reagent. Cellulase activity was calculated based on a glucose standard curve and reported as $\text{mg glucose g}^{-1} 72 \text{ h}^{-1}$.

Urease activity was analyzed using the phenol–hypochlorite colorimetric procedure as described by Tabatabai and Bremner (1972) [21]. A 10 g fresh soil sample was incubated at 37°C for 24 h with toluene, urea solution, and citrate buffer to facilitate urea hydrolysis. After incubation, the mixture was filtered and adjusted to a final volume of 20 mL. An aliquot of the filtrate was reacted with sodium phenate and sodium hypochlorite, shaken thoroughly, and allowed to develop color for 20 min. Absorbance was measured at 578 nm, and urease activity was calculated from an NH_4^+-N standard curve and expressed as $\text{mg NH}_4^+-\text{N g}^{-1} 24 \text{ h}^{-1}$.

Alkaline phosphatase activity was determined using p-nitrophenyl phosphate (pNPP) as the reaction substrate following the method of Tabatabai and Bremner (1969) [22]. A 5 g fresh soil sample was combined with toluene, pNPP solution, and alkaline buffer (pH 11), and the mixture was incubated at 37 °C for 1 h. The reaction was terminated by adding NaOH, followed by filtration. The released p-nitrophenol (pNP) in the filtrate was measured spectrophotometrically at 405 nm. Alkaline phosphatase activity was calculated from a pNP standard curve and expressed as $\mu\text{mol pNP g}^{-1} \text{ h}^{-1}$.

2.3.4. Determination of Cotton Biomass and Root Activity

At the flowering–boll stage, cotton shoot and root biomass, root-to-shoot ratio, and root activity were determined. For each treatment, five cotton plants were randomly selected from three sampling areas, each measuring 3.0 m $\times$ 2.05 m. The aboveground biomass (shoot biomass) was collected by cutting the plants at the soil surface, including stems, leaves, and any unharvested bolls. The roots were carefully excavated from the soil using a hand shovel to avoid damaging the root system, then cleaned gently with water to remove any soil particles. Both the shoot and root biomass samples were air-dried, then oven-dried at 75 °C for 48 h until constant weight was achieved, to determine the dry weight (kg plant^{-1}).

The root-to-shoot ratio was calculated by dividing the dry weight of the roots by the dry weight of the shoots. Root activity was determined using the 2,3,5-triphenyltetrazolium chloride (TTC) reduction assay. For each treatment, root samples were collected from the 0–20 cm and 20–40 cm soil layers, cleaned to remove adhering soil particles, and incubated with a substrate solution at 37 °C for 24 h. The resulting root activity was expressed as $\mu\text{g TPF}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$, representing the metabolic activity of the roots during the incubation period [23]. The mean values of all parameters were calculated from the five representative plants in each plot and used for further analysis.

2.3.5. Determination of Cotton Yield: Its Components

At the cotton harvesting stage, yield and its components were determined. All plants from three randomly selected areas (each 3.0 m $\times$ 2.05 m) per plot were harvested to measure the total seed cotton yield. Concurrently, five representative plants were randomly selected from each plot for individual plant analysis. The following parameters were recorded for each plant: the total number of bolls (bolls per plant), the seed cotton weight per plant, and the lint percentage after ginning. The average boll weight was calculated as the seed cotton weight per plant divided by the number of bolls per plant. The mean values of these components from the five plants were used for each plot.

2.4. Statistical Analysis and Plotting

A one-way analysis of variance (ANOVA) was conducted using R (version 4.3.2) to examine the effects of the treatment as a fixed factor on cotton traits. Post hoc multiple comparisons were performed using the Least Significant Difference (LSD) test at a significance level of $p < 0.05$. Data presented in figures and tables represent the means of three replicates per treatment. Figures were generated using R (version 4.3.2) with the ggplot2 package for graphical visualizations, while tables were prepared in Microsoft Excel 2021 (Microsoft Corp., Redmond, WA, USA). In addition, Microsoft PowerPoint 2021 (Microsoft Corp., Redmond, WA, USA) was used to compile and present the figures. The Random Forest regression model, conducted using the randomForest and rfPermute packages in R, was employed to assess variable importance and model significance, with the results evaluated using permutation tests. Structural equation modeling (SEM) was performed using PLS-PM via the plsmpm package in R. Model quality was evaluated using path coefficients, goodness of fit (GOF), R^2 values of endogenous constructs, and, where applicable, measurement

quality indicators including average variance extracted (AVE), composite reliability (CR), predictive relevance (Q^2), and the standardized root mean square residual (SRMR).

3. Results

3.1. Soil Physical and Chemical Properties

Figure 2 illustrates the variation in soil physical and chemical properties in 2024 and 2025. Two-way ANOVA (Table S1) showed that treatment was the main source of variation for all four variables at both depths, as indicated by significant treatment effects on bulk density ($F = 45.10$ and 27.44 at 20 and 40 cm, respectively; $p < 0.001$), SOC ($F = 26.30$ and 25.26 ; $p < 0.001$), and NO_3^- -N ($F = 50.26$ and 66.51 ; $p < 0.001$), whereas year effects were limited and treatment $\times$ year interactions were generally not significant. As shown in Figure 2a, bulk density in the 0 – 20 cm layer was generally lower than in the 20 – 40 cm layer. Across both years, lower bulk density values were mainly observed under the PAM and PAM + HA treatments. Specifically, in 2024, the bulk density under PAM in the 0 – 20 cm layer was $1.43 \text{ g}\cdot\text{cm}^{-3}$, significantly lower than that under CK ($1.56 \text{ g}\cdot\text{cm}^{-3}$, $p < 0.05$). In 2025, the differences between treatments remained evident, although soil bulk density at 40 cm was slightly higher overall, consistent with the significant year effect detected by ANOVA for this layer ($F = 13.44$, $p = 0.0021$). Soil pH (Figure 2b) was lower under HA-, PAM-, and PAM + HA-containing treatments than under CK at both depths. In 2024, PAM + HA treatment resulted in a pH of 7.88 in the 0 – 20 cm layer, significantly lower than that under CK (8.35 , $p < 0.05$). In 2025, pH values remained lower under HA- and PAM + HA-containing treatments, and the treatment pattern was generally similar to that in 2024. ANOVA further showed that treatment significantly affected pH at both depths, whereas year and treatment $\times$ year effects were not significant. Soil organic carbon (Figure 2c) was higher under HA- and PAM + HA-containing treatments than under CK. In the 0 – 20 cm layer, PAM + HA treatment showed SOC values of 3.29 and $4.29 \text{ g}\cdot\text{kg}^{-1}$ in 2024 and 2025, respectively, and the 2025 value was significantly higher than that under CK ($p < 0.01$). Nitrate nitrogen (NO_3^- -N) content (Figure 2d) also varied significantly among treatments. PAM + HA treatment showed the highest values at both depths in both years, reaching 25.51 and $30.27 \text{ mg}\cdot\text{kg}^{-1}$ in the 0 – 20 cm layer in 2024 and 2025, respectively; both values were significantly higher than those under CK ($p < 0.05$). PAM treatment also maintained relatively high NO_3^- -N content, especially in 2024.

Figure 3 shows the proportions of soil aggregates across different treatments and particle size categories. Treatment differences were observed mainly in the >2 mm and 0.25 – 2 mm fractions. In both 2024 and 2025, PAM + HA showed the highest proportion of aggregates >2 mm (3.60% and 3.24% , respectively), whereas CK showed the lowest values (1.18% and 2.25% , respectively); the proportion under PAM + HA was significantly higher than that under CK ($p < 0.05$). For the 0.25 – 2 mm fraction, PAM and PAM + HA showed higher proportions than CK, with PAM + HA reaching 26.65% in 2025, significantly higher than CK (14.04% , $p < 0.05$). In contrast, CK maintained a relatively high proportion in the 0.053 – 0.25 mm fraction, whereas PAM + HA showed lower values. For the <0.053 mm fraction, CK had the highest proportion (37.95%), while PAM showed the lowest value (32.29%).

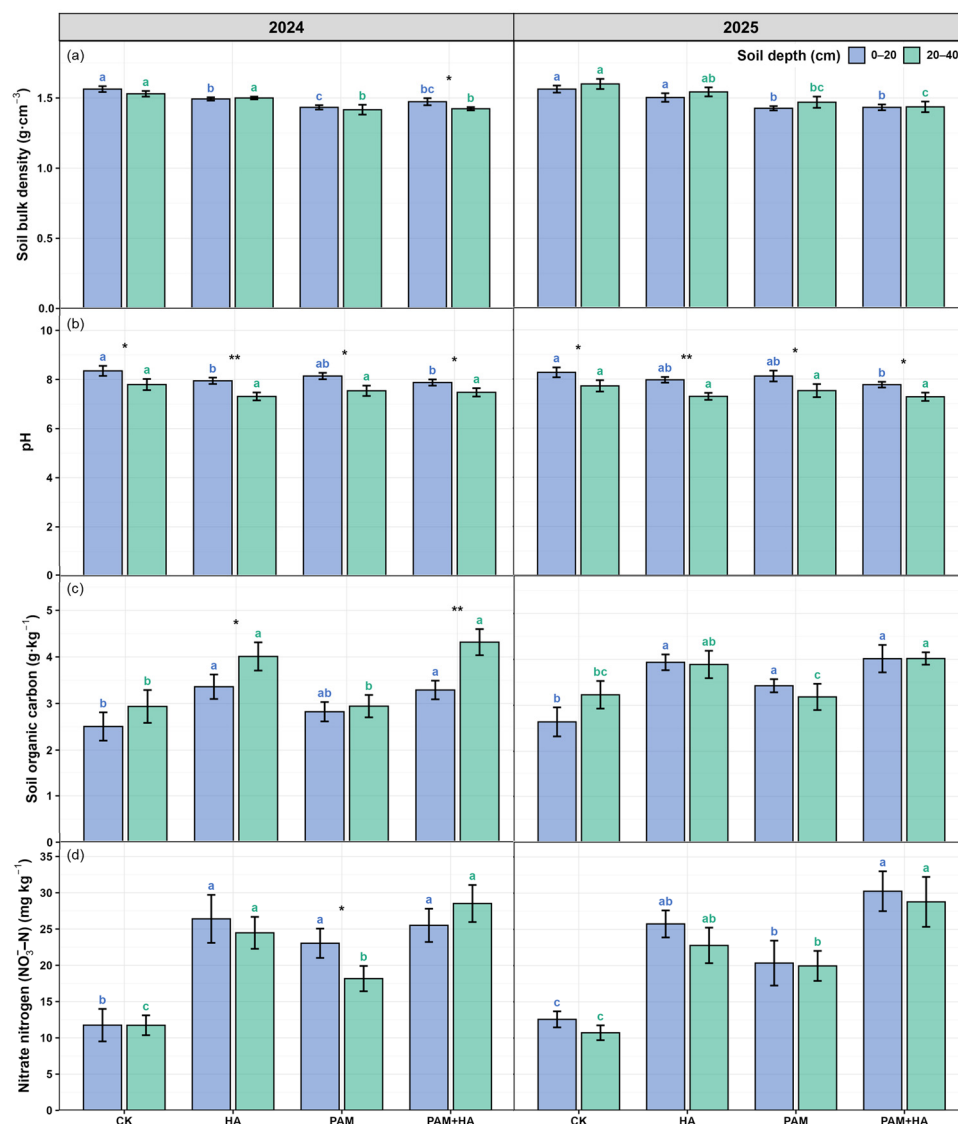


Figure 2. Effects of soil depth and treatments on soil physical and chemical properties in 2024 and 2025. The graphs show the effects of different treatments (CK, HA, PAM, and PAM + HA) and soil depth (0–20 cm and 20–40 cm) on soil bulk density (a), pH (b), soil organic carbon (SOC) (c), and nitrate nitrogen ($\text{NO}_3\text{-N}$) (d) in the years 2024 and 2025. Different letters indicate significant differences between treatments ($p < 0.05$). Error bars represent the standard error of the mean. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$.

3.2. Soil Enzyme Activities

The results of soil enzyme activities measured at the flowering–boll stage at two soil depths (0–20 cm and 20–40 cm) are summarized in Figure 4. Two-way ANOVA (Table S1) showed that treatment significantly affected cellulase, amylase, urease, and alkaline phosphatase activities at both depths (all $p < 0.001$), whereas year and treatment $\times$ year effects were not significant. For cellulase (Figure 4a), higher activities were generally observed under PAM + HA and HA than under CK at both depths. In the 0–20 cm layer, cellulase activity under PAM + HA reached $16.85 \text{ mg glucose g}^{-1} 72 \text{ h}^{-1}$ in 2024, significantly higher than that under CK ($6.17 \text{ mg glucose g}^{-1} 72 \text{ h}^{-1}$, $p < 0.05$). At 20–40 cm, CK remained the lowest treatment group. For amylase (Figure 4b), higher values were generally observed under PAM + HA and HA than under CK. In the 0–20 cm layer, PAM + HA reached $9.55 \text{ mg glucose g}^{-1} 24 \text{ h}^{-1}$ in 2024, significantly higher than CK ($3.62 \text{ mg glucose g}^{-1} 24 \text{ h}^{-1}$, $p < 0.05$). For urease (Figure 4c), PAM + HA and HA showed higher activities than

CK and PAM. In the 0–20 cm layer, PAM + HA reached $5.25 \text{ mg NH}_4^+-\text{N g}^{-1} \text{ 24 h}^{-1}$ in 2024, significantly higher than CK ($3.62 \text{ mg NH}_4^+-\text{N g}^{-1} \text{ 24 h}^{-1}$, $p < 0.05$). At 20–40 cm, urease activity remained lower under CK than under the amendment treatments. For alkaline phosphatase (Figure 4d), PAM + HA and HA also showed higher values than CK. In the 0–20 cm layer, alkaline phosphatase activity under PAM + HA reached $0.72 \text{ } \mu\text{mol pNP g}^{-1} \text{ h}^{-1}$ in 2024, significantly higher than that under CK ($0.42 \text{ } \mu\text{mol pNP g}^{-1} \text{ h}^{-1}$, $p < 0.01$). A similar difference among treatments was observed at 20–40 cm.

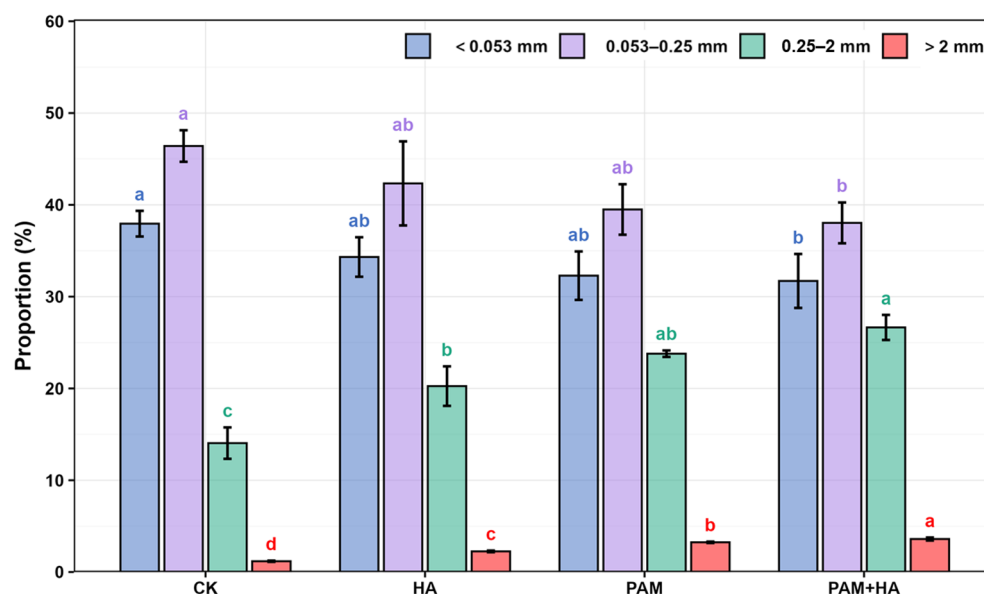


Figure 3. Effects of treatment on soil aggregate size distribution in 2024 and 2025. The bar graphs display the proportions of soil aggregates larger than 2 mm, between 0.25–2 mm, between 0.053–0.25 mm, and smaller than 0.053 mm in the topsoil (0–20 cm) for different treatments (CK, HA, PAM, and PAM + HA) in 2024 and 2025. Significant differences between treatments are indicated by different letters ($p < 0.05$). Error bars represent standard errors.

3.3. Root Traits and Yield

The results for shoot dry weight, root dry weight, root activity, and root-to-shoot ratio are shown in Figure 5. Two-way ANOVA (Table S1) showed that treatment significantly affected shoot dry weight, root dry weight, and root activity, whereas year significantly affected root activity only; treatment $\times$ year interactions were not significant. In contrast, no significant effects were detected for the root-to-shoot ratio. For shoot dry weight (Figure 5a), PAM + HA had the greatest shoot dry weight in both 2024 and 2025, reaching 9776.3 and $10,092.8 \text{ kg} \cdot \text{ha}^{-1}$, respectively. In both years, shoot dry weight under PAM + HA was significantly higher than that under CK ($p < 0.05$), whereas HA and PAM showed intermediate values. For root dry weight (Figure 5b), PAM + HA also showed the highest values, with $1500.7 \text{ kg} \cdot \text{ha}^{-1}$ in 2024 and $1553.0 \text{ kg} \cdot \text{ha}^{-1}$ in 2025. In both years, root dry weight under PAM + HA was significantly higher than that under CK ($p < 0.05$), whereas HA and PAM showed intermediate values. Root-to-shoot ratio (Figure 5d) varied only slightly among treatments and years, and no significant treatment, year, or interaction effects were detected by ANOVA. Root activity (Figure 5c) was highest under PAM + HA in both years, reaching $152.67 \text{ } \mu\text{g TPF} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ in 2024 and $162.00 \text{ } \mu\text{g TPF} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ in 2025. These values were significantly higher than those under CK ($p < 0.05$). ANOVA further showed a significant year effect for root activity ($F = 40.32$, $p < 0.001$), indicating generally higher values in 2025 than in 2024.

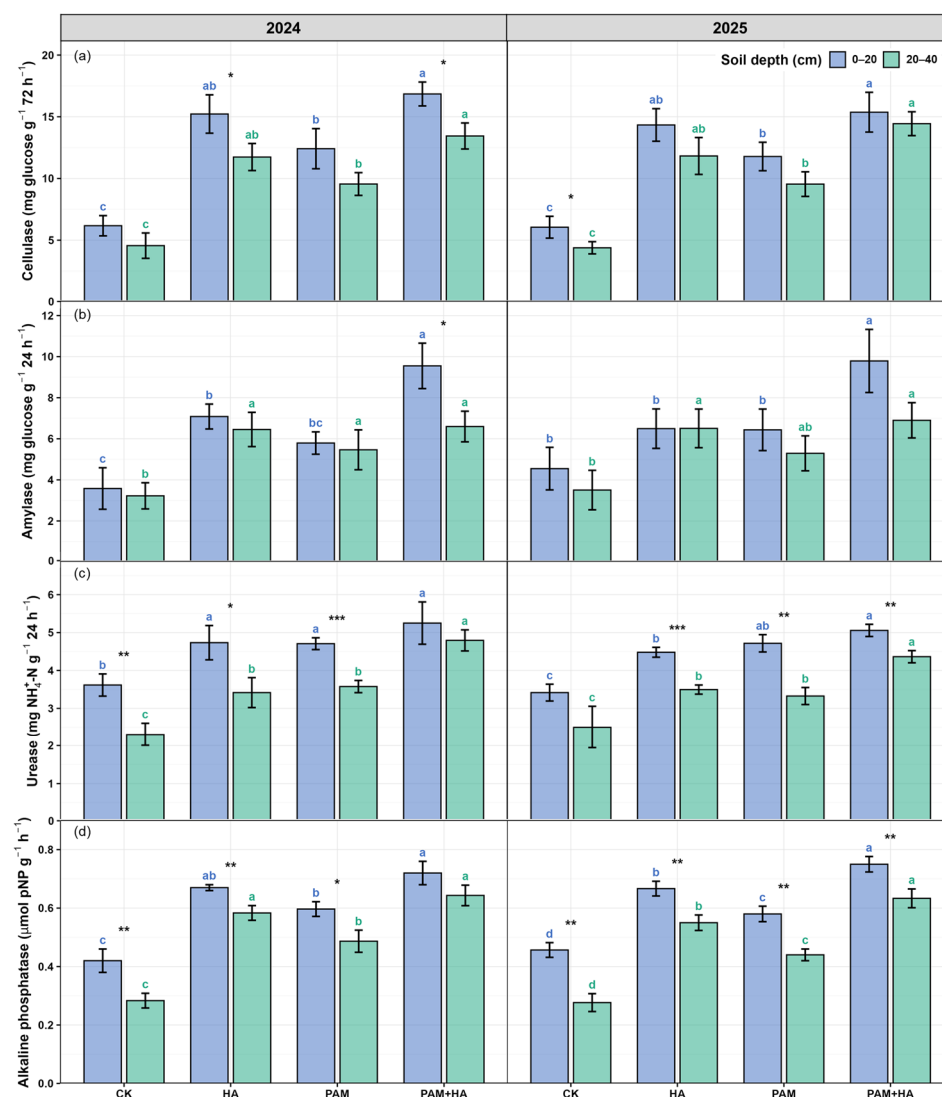


Figure 4. Effects of treatment on soil enzyme activity in 2024 and 2025. The graphs show the activity of four soil enzymes: cellulase (a), amylase (b), urease (c), and alkaline phosphatase (d) in the topsoil (0–20 cm) and subsoil (20–40 cm) layers under different treatments (CK, HA, PAM, and PAM + HA) in the years 2024 and 2025. Significant differences between treatments are represented by different letters ($p < 0.05$). Error bars indicate the standard error of the mean. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 6 shows the results for yield, boll number, boll weight, and lint percentage. Two-way ANOVA (Table S1) showed that treatment significantly affected all four variables, whereas year and treatment $\times$ year interaction were significant only for yield. For yield (Figure 6a), PAM + HA showed the highest value in 2024 ($6683.69 \text{ kg} \cdot \text{ha}^{-1}$), significantly higher than CK ($4427.00 \text{ kg} \cdot \text{ha}^{-1}$, $p < 0.05$). In 2025, PAM + HA also remained among the highest-yielding treatments, with a value of $5996.89 \text{ kg} \cdot \text{ha}^{-1}$, whereas CK remained the lowest. ANOVA further showed significant effects of year ($F = 8.58$, $p = 0.0098$) and treatment $\times$ year interaction ($F = 4.08$, $p = 0.0249$) on yield. Boll number (Figure 6c) was higher under PAM + HA, HA, and PAM than under CK, with PAM + HA reaching 5.95 and 5.92 bolls $\cdot \text{plant}^{-1}$ in 2024 and 2025, respectively. For single boll weight (Figure 6d), PAM + HA showed the highest values in both years, reaching 5.34 g in 2024 and 5.53 g in 2025. Treatment significantly affected single boll weight, whereas year and treatment $\times$ year effects were not significant. Lint percentage (Figure 6b) varied within a relatively narrow range across treatments. Although the treatment effect was significant in

the ANOVA ($p = 0.0371$), the differences among treatments were small, with slightly higher values observed under PAM + HA than under CK.

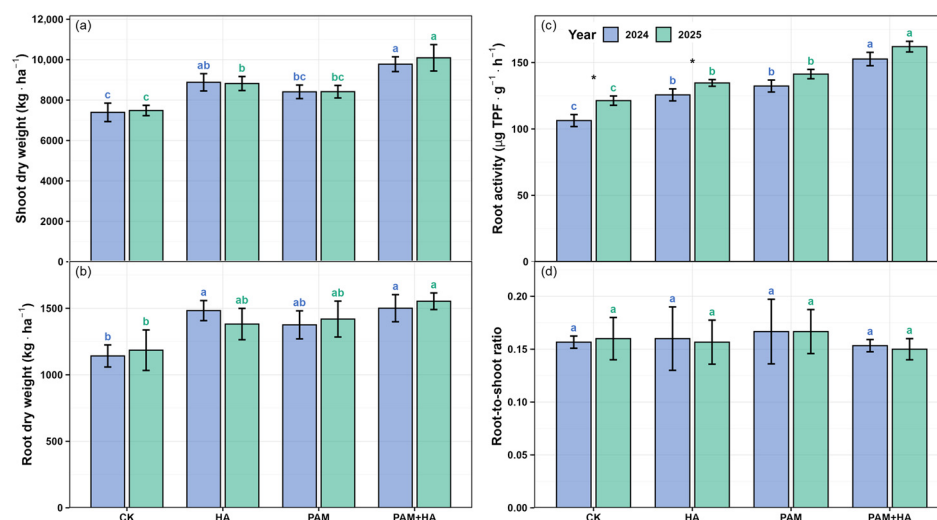


Figure 5. Effects of treatment on root and shoot growth in 2024 and 2025. The bar graphs show the shoot dry weight (a), root dry weight (b), root activity (c), and root-to-shoot ratio (d) in the topsoil (0–20 cm) for different treatments (CK, HA, PAM, and PAM + HA) in 2024 and 2025. Statistical significance is denoted by different letters ($p < 0.05$). Error bars represent the standard error. Significance levels are indicated as * $p < 0.05$.

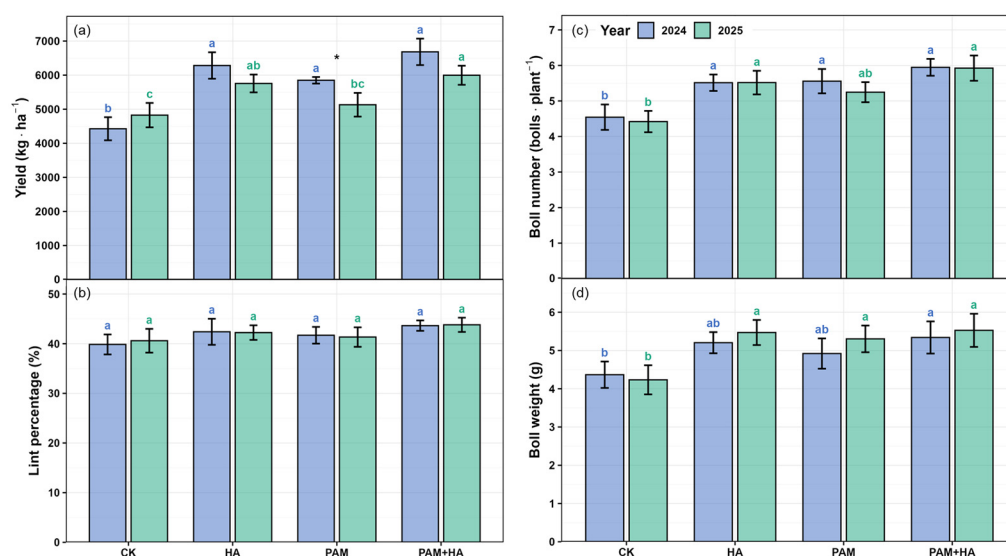


Figure 6. Effects of treatment on cotton yield and related parameters in 2024 and 2025. The graphs present cotton yield (a), boll number per plant (b), boll weight (c), and lint percentage (d) under different treatments (CK, HA, PAM, and PAM + HA) in 2024 and 2025. Significant differences between treatments are indicated by different letters ($p < 0.05$). Error bars represent the standard error of the mean. Significance levels are indicated as * $p < 0.05$.

3.4. The Relationship Between Soil Factors and Cotton Yield

The results presented in Figure 7 reflect the SEM and random forest analysis results. In the PLS-PM model (a), treatment exerted strong positive effects on soil structure ($\beta = 0.89$, 95% CI: 0.78–0.95, $p < 0.001$) and soil fertility ($\beta = 0.62$, 95% CI: 0.31–0.84, $p = 0.003$). Soil fertility strongly promoted enzyme activity ($\beta = 0.74$, 95% CI: 0.51–0.89, $p < 0.001$), whereas soil structure had a weaker but significant direct effect on enzyme activity ($\beta = 0.24$, 95% CI: 0.03–0.46, $p = 0.031$). Enzyme activity significantly promoted root development ($\beta = 0.65$,

95% CI: 0.18–0.87, $p = 0.012$), and root development exerted the strongest direct positive effect on yield ($\beta = 0.79$, 95% CI: 0.52–0.91, $p < 0.001$). In contrast, the paths from soil structure to soil fertility ($\beta = 0.30$, $p = 0.118$) and from soil fertility to root development ($\beta = 0.31$, $p = 0.094$) were not significant. The explained variance (R^2) was 0.79 for soil structure, 0.81 for soil fertility, 0.93 for enzyme activity, 0.76 for root development, and 0.63 for yield, with an overall goodness of fit (GOF) of 0.74. In addition, the measurement and predictive quality of the PLS-PM model were acceptable, with AVE values ranging from 0.64 to 0.74, CR values from 0.84 to 0.90, Q^2 values from 0.36 to 0.58, and an SRMR of 0.071.

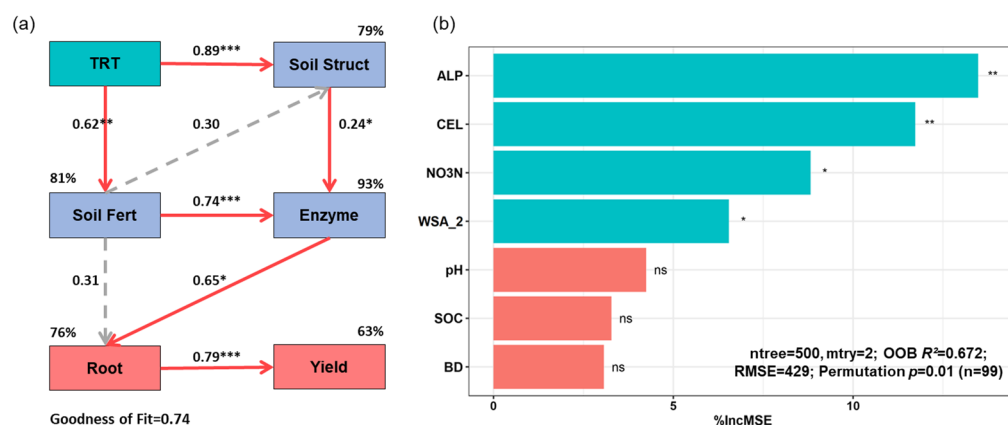


Figure 7. Structural equation model (SEM) of soil–root–yield relationships and random forest analysis of key soil predictors of cotton yield. (a) The SEM illustrates the relationships among treatment, soil structure, soil fertility, enzyme activity, root development, and yield. Numbers on arrows are standardized path coefficients; solid red arrows indicate significant paths and dashed gray arrows indicate non-significant paths. Values in boxes represent R^2 , and GOF is shown below the model. (b) The random forest model shows the relative importance of soil variables for predicting cotton yield (%IncMSE). Model parameters (ntree, mtry, OOB R^2 , RMSE, and permutation p -value) are reported in the panel. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ns, not significant.

As a complementary analysis to the SEM, the random forest model was used to identify and rank the key soil predictors of cotton yield within the overall soil–root–yield framework. Alkaline phosphatase (ALP), cellulase (CEL), and nitrate nitrogen (NO_3N) were identified as the most important predictors of yield, followed by WSA_2. In contrast, pH, SOC, and bulk density contributed less to model performance. The random forest model showed an out-of-bag (OOB) R^2 of 0.672 and an RMSE of 429, and the permutation test was significant ($p = 0.01$, $n = 99$), supporting the predictive relevance of the selected soil variables.

4. Discussion

In this study, PAM-containing treatments reduced soil bulk density and increased the proportion of larger aggregates in the 0–20 cm layer, showing that PAM mainly influenced the physical organization of the saline–sodic root zone. Similar responses have been reported for structure-oriented amendments in salt-affected soils, where lower bulk density and improved pore continuity enhance infiltration and aeration [24]. In saline–sodic soils, such structural improvement is closely associated with greater porosity, better air–water flow, lower mechanical impedance, and improved conditions for root exploration [25]. At the chemical and interfacial level, PAM, especially partially hydrolyzed anionic PAM, contains abundant amide groups ($-\text{CONH}_2$) and partially hydrolyzed carboxyl/carboxylate groups ($-\text{COOH}/-\text{COO}^-$) along its molecular chains [26]. These functional groups interact with clay particles, silt particles, and organic colloids through hydrogen bonding, van der Waals forces, and cation bridging, particularly with Ca^{2+} and Mg^{2+} . This process

forms polymer bridging among dispersed fine particles and promotes flocculation and aggregate stabilization [27]. Under saline–sodic conditions, where Na^+ dominance expands the diffuse double layer, enhances colloidal dispersion, destabilizes aggregates, and disrupts pore continuity, PAM counteracts the dispersion trend and thereby moves the soil toward a more flocculated and structurally stable state [28]. As a result, the improved pore system and more stable aggregate framework provide more favorable microsites for microbial colonization, enzyme preservation, water movement, and root extension, thereby strengthening the physical foundation of root-zone functioning.

In this study, HA-containing treatments were more strongly associated with lower pH and higher SOC and $\text{NO}_3^- - \text{N}$ than CK, indicating that HA mainly regulated the chemical and biochemical environment of the alkaline root zone. Humic substances are well known to improve soil quality and support aggregate persistence [29], but their more distinctive role in the present study was the improvement of fertility-related pools and nutrient transformation processes. At the chemical level, humic acid contains abundant carboxyl groups and phenolic hydroxyl groups, which contribute to weak acidification, cation exchange, buffering, and complexation reactions in alkaline soils [30,31]. These reactions help lower pH, improve nutrient retention, and increase the availability of nutrients that are otherwise constrained by precipitation and buffering in alkaline systems [8]. Higher SOC further strengthens cation retention, buffering capacity, and resistance to ionic stress and nutrient loss in saline soils [32]. At the same time, the organic carbon introduced by HA supports microbial metabolism and nutrient turnover. Organic inputs enhance N mineralization, and when aeration and moisture conditions are favorable, the resulting NH_4^+ is more readily nitrified, increasing $\text{NO}_3^- - \text{N}$ supply in the root zone [33,34]. This chemical and biological activation is consistent with the higher cellulase, amylase, urease, and alkaline phosphatase activities observed in HA-containing treatments, since these enzymes reflect enhanced turnover of C, N, and P under improved substrate supply and microbial activity [35,36].

In this study, the combined PAM + HA treatment produced the most integrated response in the root zone, including lower bulk density and pH, a greater proportion of larger aggregates, higher SOC and $\text{NO}_3^- - \text{N}$, and stronger enzyme activities than the single-application treatments. This pattern is consistent with a coupled mechanism in which PAM mainly stabilized the physical framework of the soil, whereas HA mainly enhanced the chemical and biochemical environment [12]. From a chemical and interfacial perspective, PAM contributes polymer bridging and flocculation through adsorption of its amide and partially hydrolyzed carboxylate groups onto soil particles and colloids, while HA contributes carboxyl- and phenolic hydroxyl-rich functional groups that participate in weak acidification, cation exchange, buffering, and complexation [37,38]. When applied together, these two types of interaction act simultaneously on both the physical structure and the chemical reactivity of the root-zone soil. Similar synergistic effects have been reported for humic acid–acrylamide polymer systems [39], which improved aggregate formation and pore characteristics more effectively than single polymers alone. More broadly, humic substances are also known to enhance soil aggregation, buffering, nutrient bioavailability, and microbial functioning [40]. Under saline–sodic conditions, this coupled action is particularly important because Na^+ promotes colloidal dispersion and pore disruption, whereas the combined amendment simultaneously promotes flocculation, aggregate stabilization, nutrient retention, and biochemical activity [41].

The macroscopic consequences of this coupled regulation were expressed in root development and yield formation. In the present study, PAM + HA increased both root dry mass and root activity, indicating that the combined amendment alleviated multiple root-zone constraints simultaneously. Lower bulk density and greater pore continuity reduced

mechanical impedance to root extension, improved aeration supported root respiration, and enhanced nutrient transformation, reducing the physiological costs of ion homeostasis and resource acquisition under saline–sodic stress [42–44]. These improvements were accompanied by higher seed cotton and lint yield, which is consistent with the view that a more favorable root-zone environment stabilizes water and nutrient supply, sustains reproductive development, and supports boll retention, boll weight, and lint formation under salt stress [45,46]. The structural model further supported this pathway: treatment effects on yield were linked to changes in soil structure and fertility, which then promoted root development, and root development showed the strongest direct association with yield (standardized effect = 0.79; GOF = 0.74). The random forest results were consistent with this pathway, ranking alkaline phosphatase, cellulase, and NO_3^- -N as the most important predictors of yield variation. These variables reflect biologically mediated P recycling, microbial turnover of C substrates, and immediately available N supply, respectively [47,48]. Their prominence suggests that the combined amendment strengthened the biochemical functioning of the rhizosphere, especially the processes governing nutrient release, nutrient turnover, and nutrient supply to roots [49]. This interpretation is also consistent with the observed increases in aggregate stability, SOC, and enzyme activities under PAM + HA, because a more stable aggregate framework can protect microbial habitats and extracellular enzymes [50], while a more favorable chemical environment can enhance substrate availability, buffering, and nutrient transformation in the root zone [51]. In this sense, root development represented the most direct biological pathway to yield formation, whereas enzyme-related variables and NO_3^- -N reflected the soil biochemical conditions that supported this pathway [52].

5. Conclusions

This two-year field study shows that polyacrylamide (PAM) soil conditioner and humic acid (HA), especially in combination (PAM + HA), consistently improved key soil and crop outcomes in saline–sodic cotton fields. Compared with the control, PAM and PAM + HA reduced bulk density and pH in the 0–20 cm layer, shifted aggregate size distribution toward larger fractions, and increased SOC and NO_3^- -N. PAM + HA also produced the strongest increases in enzyme activities (cellulase, amylase, urease, and alkaline phosphatase), and it achieved the highest root biomass, root activity, and yield across both years. The SEM results support that treatment effects on yield were statistically linked to changes in soil structure and fertility and then to root development, while the random forest analysis identified ALP, cellulase, and NO_3^- -N as the most important predictors of yield variation. Under the conditions of this two-year field experiment, PAM + HA represented the most favorable integrated amendment strategy for alleviating root-zone constraints and supporting cotton production in this saline–sodic cotton field. These findings indicate that coordinated regulation of soil structure, nutrient transformation, and root-zone functioning is a key direction for amendment management in salt-affected cotton systems, and future studies should further test the robustness of this strategy across sites, years, and salinity levels.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/w18070780/s1>. Table S1: Two-way ANOVA results for the effects of treatment, year, and their interaction on soil, root, and yield-related variables.

Author Contributions: Y.G., X.M. and G.M. participated in the conceptualization and design of the study. Y.G. and J.Z. conducted the field experiments and laboratory analyses. Y.G. performed the data analysis and drafted the original manuscript. Z.W. supervised the research, provided critical

revisions, and was responsible for project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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