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Article | Open access | Published: 06 May 2025

Effects of biochar combined with the application of plant ash and effective microorganisms on the soil in the vegetable facility

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Scientific Reports **15**, Article number: 15824 (2025)

A Publisher Correction to this article was published on 06 August 2025

This article has been updated

Abstract

In facility agriculture, soil barriers have led to severe soil quality degradation, making it crucial to take effective measures for soil improvement. This research focuses on exploring the impacts of biochar, plant ash, and Effective Microorganisms (EM) on the physical, chemical properties, and nutrient levels of facility-agriculture soil, aiming to find a novel and efficient solution to address the soil-related issues. A field trial was carried out to assess the combined application of biochar, EM bacteria, and plant ash on soil properties. The experiment setup consisted of a blank control (CK) and six treatment groups (T_1–T_6) with different dosage gradients. The combined application of biochar, plant ash and EM bacteria significantly enhanced various soil properties. Specifically, the pH, soil bulk density, total nitrogen, total phosphorus, total potassium, organic matter, alkaline hydrolyzed nitrogen, available phosphorus, and available potassium levels in facility-agriculture soil increased by 1.1-24.0%, 6.09-9.83%, 32.22-61.26%, 11.82-47.82%, 1.44-6.99%, 19.42-77.23%, 10.64-44.09%, 22.01-49.71%, and 14.11-93.64% respectively. The soil comprehensive fertility index (*IFI*) showed that this combined application could effectively improve the comprehensive soil fertility, with the T_4 treatment (plant ash 3030 kg/hm^2 + biochar 6060 kg/hm^2 + EM bacteria 37.5:1) demonstrating the best improvement effect. The combined application of biochar, EM bacteria and plant ash can overcome the soil barriers in facility agriculture, mitigate soil acidification and nutrient disorders, promote nutrient supply, and enhance soil fertility. The study

Introduction

In recent years, facility agriculture has witnessed remarkable growth. In Chian, the area of facility agriculture has surpassed 63 million mu, with facility vegetable cultivation being the dominant focus[1,2,3]. This expansion has been crucial for meeting the increasing demand for fresh vegetables, especially during off-season periods. However, the development of facility vegetable cultivation has been accompanied by a series of intractable problems.

The prevalent use of irrational irrigation and fertilization patterns, along with long-term heavy cropping and continuous monoculture, has led to a significant decline in the physical and chemical properties of facility vegetable soils. This degradation is manifested in nutrient imbalance, and the rampant breeding and spread of various soil-borne diseases[4]. As a consequence, facility vegetables often suffer from nutritional imbalance, developmental disorders, reduced cultivation quality, and even yield losses[5]. These issues not only pose a threat to the sustainable development of facility agriculture but also have implications for food security and the economic well-being of farmers. As a result, they have drawn the attention of government agricultural management departments and the scientific community, prompting extensive research on soil barriers in facility vegetables and the exploration of effective control measures.

Previous research efforts have focused on a variety of approaches, including altering planting and fertilization methods, adopting scientific irrigation and tillage practices, and regulating soil conditions through agronomic, biological, or chemical means. These measures also involve increasing the application of organic fertilizers and biofungal fertilizers, as well as using soil rejuvenators or amendments. To some extent, these strategies have improved the soil environment for facility agriculture and mitigated the challenges associated with continuous cropping. However, there is still a pressing need for more effective and sustainable solutions.

combination of biochar and biological bacteria has shown great potential in reducing soil-borne diseases, alleviating continuous cropping obstacles, improving soil physical and chemical properties, and increasing soil total organic carbon and alkali-hydrolyzed nitrogen content[10,11,12].

Plant ash, rich in potassium, calcium, and phosphorus, has unique physical and chemical properties. It has a large porosity and excellent water - retention capacity, and also functions in disinfection, potassium supplementation, and supplying trace elements[13,14,15]. EM bacteria, a mixture of beneficial microorganisms, can balance the soil microbial community structure, inhibit the reproduction of harmful pathogens, mediate the soil microbial ecological environment, enhance crop disease resistance and immunity, and improve crop growth, yield, and quality[16,17,18]. Previous studies[19] have demonstrated that the combined application of plant ash, biochar, and EM bacteria can effectively address soil acidification, improve the fertility of facility vegetable planting soil, and enhance the quality of tomatoes.

Taibai County in Baoji City, Shaanxi Province, is a vital production area for high-mountain off-season green and pollution-free vegetables, with the vegetable planting area accounting for over 80% of the agricultural area. Facility vegetable cultivation is the primary mode of high-mountain off-season green pollution-free vegetable production in Taibai County. In recent years, as facility vegetable cultivation has become increasingly popular, the problems associated with facility vegetable soil have become more prominent.

Building on previous research that has confirmed the positive effects of the plant ash + biochar + EM bacteria combination on improving facility vegetable soil quality and promoting crop production, this study takes the soil of vegetable greenhouses in Qinxi demonstration garden in Taibai County as a pilot. By applying plant ash + biochar + EM bacteria as a mixed amendment, the study aims to systematically investigate the effects of different application dosages of this combination on the basic physical and chemical properties and nutrient content of facility vegetable soil. The overarching goal is to identify the optimal application dosage of plant ash biochar + EM bacteria, providing practical methods, technical references, and a theoretical basis for facility vegetable planting in Taibai County and, more broadly, for soil improvement in facility vegetable cultivation across the nation. This research not only contributes to the sustainable development of facility agriculture in a specific region but also has the potential to inform best practices for soil management in facility vegetable production on a national scale, thus filling a critical knowledge gap in the field of agricultural science.

Research materials and methods

Soil overview of the research

The research plot is situated at the vegetable planting demonstration base of Qinxi Agriculture and Forestry Development Co., Ltd., in Taibai County, Baoji City, Shaanxi Province (33°38′13″–34°09′55″N, 107°03′00″–107°46′40″E). The soil types in the test area are predominantly brown soil, fluvo-aquic soil, and silt soil, as reported by Kang[20]. During the improvement plan screening stage, Vegetable Greenhouse #7 in the

4.5, soil porosity 28.6%, bulk density 1.9 g/cm^3, soil organic matter content 31.2 g kg^{-1}, total nitrogen 2.4 g kg^{-1}, total phosphorus 1.6 g kg^{-1}, total potassium 21.1 g kg^{-1}, alkaline hydrolyzed nitrogen 162.0 mg kg^{-1}, available phosphorus 296.6 mg kg^{-1} and available potassium 118.6 mg kg^{-1}.

Research materials

The tomato variety used in this study is “Provence”, which was purchased and nursed at the demonstration base. This variety is well - known for its adaptability to greenhouse cultivation and high-yield potential, making it suitable for the research objectives. The biochar was sourced from a manufacturer. It was produced through the combustion of corn straw and has a particle size of 200 mesh. The biochar has an ash content of 3%, a moisture content of 10%, a combustion temperature range of 300–400 °C, and a filling density of 420–480 kg (G/L). The acid-soluble iron content is 0.03% and the acid-soluble ash is 3%. These properties are crucial for understanding its impact on soil fertility and plant growth. The plant ash was obtained from the local village, with waste wood and straw as raw materials. Analysis of the ash revealed a moisture content of 4%, loss on ignition of 1.63%, CaO content of 35%, K_2O content of 15.5%, SiO_2 content of 15.3%, MgO content of 9%, P_2O_5 content of 6.1%, Al_2O_3 content of 3.1%, and Fe_2O_3 content of 2.1%. The composition of plant ash determines its role as a soil amendment. The EM bacteria were purchased from Shanghai Sansheng Biotechnology Co., Ltd. The main components of EM were mixed strains of photosynthetic bacteria, yeast, Bacillus, Bifidobacterium, and lactic acid bacteria, with an effective number of viable bacteria ≥ 20 billion mL^{-1}. These bacteria play a significant role in soil micro-ecological regulation.

Research design

Considering the prevalent issues faced by facility vegetables, this study selected the vegetable planting demonstration base of Qinxi Agricultural and Forestry Development Co., Ltd. in Taibai County as a pilot. In 2020, Greenhouse #7 of the demonstration base was utilized for screening research on improvement measures. After a series of trials, the optimal improvement plan was determined to be the combination of biochar + EM bacteria + plant ash. Subsequently, in July 2021, Greenhouse 3# of the demonstration garden, covering an area of approximately 1.5 mu (about 999 m^2, was selected for optimizing the dosage of the amendment combination and empirical research on its effects. A total of 7 treatments were established: six different dosages gradients and one blank control (CK) (see Table 1 for details). Each gradient had 3 repetitions, with each repeated block having an area of about 47.2m^2 (5.9 m×8 m). Plant ash and biochar were applied in early July, followed by mechanical plowing to a depth of approximately 25 cm to ensure thorough mixing with the soil. After a half-month contact period between the soil amendments and the soil, EM bacteria were applied, taking into account the bactericidal effect of plant ash., and the soil was plowed again to incorporate the EM bacteria. In early August, tomato seedlings (uniformly cultivated) were planted simultaneously. The plan-to-plant and row-to-row

Table 1 The experiment processing schedule.

Sample collection and processing

Soil samples were collected at different stages: before soil improvement, and during the tomato seedling, fruiting, and ending stages. In each blending gradient, three sampling points were determined using the diagonal method. At each sampling point, soil samples from the 0–20 cm and 20–40 cm layers were collected using a soil drill. In total, 42 soil samples were collected in each batch. The collected samples were placed in plastic ziplock bags, labeled, and transported to the laboratory. In a clean laboratory environment, the samples were spread out for natural air-drying. During air-drying, the soil was manually crushed, and impurities such as stones and plant roots were removed. Once air-drying to a constant weight, the soil was ground through a 100-mesh sieve, placed in kraft paper sample bags, and relabeled for future analysis.

Indicator determination

Soil pH, measured by the potentiometric method using a soil pH meter (PHSJ-3 F) with a water-to-soil ratio 2.5:1. This method provides accurate and reliable pH values, which are crucial for understanding soil acidity and its impact on nutrient availability. Soil bulk density, determined by the ring-knife method, which is a standard approach for measuring the mass of dry soil per unit volume. Organic matter content, measured by the potassium dichromate oxidation method, a widely accepted technique for quantifying soil organic matter. The total nitrogen content, determined by digestion with a mixture accelerator ($K_2SO_4 : CuSO_4 : Se = 100 : 10 : 1$), followed by the Kjeldahl method after boiling with concentrated sulfuric acid. Alkali hydrolysis nitrogen content, measured by the alkaline hydrolysis diffusion method. Total phosphorus content, determined by the NaOH fusion-molybdenum antimony colorimetric method. Available phosphorus content, measured by 0.5 mol/L $NaHCO_3$ method. Total potassium content, determined by the NaOH melt-flame photometry method. Available potassium content, determined by the NH_4OAc extraction-flame photometry method[19,21].

Data processing

The comprehensive soil fertility assessment in this study was calculated with reference to the soil Integrated Fertility Index (*IFI*) method proposed by Huo[22]. Specifically, the modified Nemerow Integrated Fertility Index (IFI_i) method was employed to evaluate soil comprehensive fertility, considering soil pH, total nitrogen, total phosphorus, total potassium, alkali nitrogen, available phosphorus, available potassium and organic matter as fertility factors. The detailed processes are as following:

The calculation formula of the Nutrient Fertility Coefficient IFI_i is as follows:

\leqslant {X_b} \hfill \\ 2+\left({X - {X_b}} \right)/\left({{X_c} - {X_b}} \right),\quad \quad {X_b} \leqslant X \leqslant {X_c} \hfill \\ 3,\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad X \leqslant {X_c} \hfill \\ \end{gathered} \right.$$

(1)

The calculation formula for the Integrated Fertility Index is as follows:

$$IFI=\sqrt {\frac{{Ave{{\left({IF{I_i}} \right)}^2}+\hbox{min} {{\left({IF{I_i}} \right)}^2}}}{2}} \left({\frac{{n - 1}}{n}} \right)$$

(2)

In the formulas, IFI_i is the nutrient fertility coefficient; X is the soil nutrient index value; X_a is the lower limit of the grading standard, X_b is the upper limit of the grading standard, and X_c is between the upper and lower limits of the grading standard. X_a, X_c, and X_p mainly refer to the selected values of the Second National Soil Survey Standards (see Table 2 for details). *IFI* is the Integrated Fertility Index. Ave (IFI_i) and Min (IFI_i) respectively represent the average and minimum values of all nutrient index sub-fertility coefficients, and n is the number of evaluation indicators.

Table 2 The grading standards of soil physical and chemical properties.

Data analyzing and mapping

Microsoft Excel 2010 software was used for data sorting and basic analysis. Origin 2021 software was employed for statistical analysis and data visualization, enabling the creation of high-quality graphs and charts to clearly present the data trends. SPSS 25.0 software was utilized for single-factor variance analysis and principal component analysis. The difference significance test was performed using the LSD method at a significance level $P < 0.05$. This suite of data analysis methods ensures a comprehensive and accurate interpretation of the research results.

Results and analysis

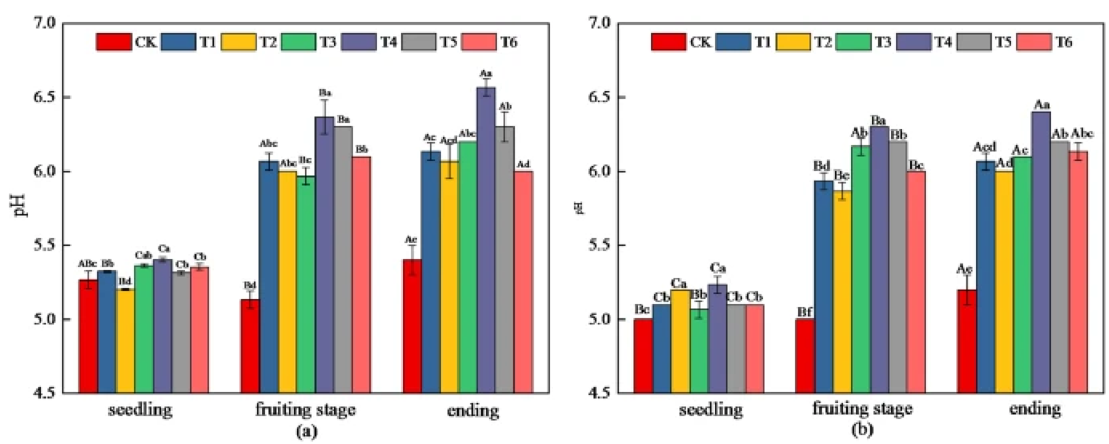
The impacts of different application dosages on the physical and chemical properties of facility soil

Impacts on facility soil pH value

The correlation between diverse application dosages and the soil pH value within a facility agricultural context represents a subject of paramount importance in contemporary agricultural research. Figure 1 meticulously implications.

At the seedling stage, a conspicuous trend becomes evident. a notable trend emerges: As the dosage of the biochar, plant ash, and EM bacteria combination increases, the soil pH demonstrates an upward inclination in compared to the blank control. Among all treatments, the T4 treatment exerts a statistically significant impact on the soil pH ($P < 0.05$). This phenomenon can be elucidated by the inherent chemical properties of the additives. Biochar, being alkaline, has the capacity to react with acidic substances in the soil, thereby neutralizing the soil acidity. Under the T4 treatment, the increase in pH by 2.59% in the 0–20 cm soil layer and 4.67% in the 20–40 cm soil layer is indicative of a substantial transformation in the soil's chemical composition at these depths. This change in pH at the seedling stage can have a profound impact on the availability of nutrients to the young plants. For instance, certain nutrients like phosphorus become more available in slightly alkaline conditions, which can enhance the early-stage growth and development of the seedlings. During the fruiting stage, the T4 treatment once again emerges as the most influential in terms of pH alteration. Across different treatments, the pH improvement ranges from spans from16.24–24.03% in the 0–20 cm soil layer and 17.33–26.00% in the 20–40 cm soil layer ($P < 0.05$). At the ending stage, all treatment significantly enhances the pH of both the 0–20 cm and 20–40 cm soil layers, with T4 being the most effective. The pH improvement range in the 0–20 cm soil layer was 11.11–21.61%, and the pH improvement range in the 20–40 cm soil layer was 15.38–23.08% ($P < 0.05$), suggesting a cumulative effect of the additive application throughout the growth cycle. Overall, with the increase in the combined application amount of biochar, plant ash and EM bacteria, each treatment increases the pH of the 0–40 cm soil layer by an average of 11.70%, 10.79%, 12.48%, 16.99%, 14.25% and 11.92%. The order of improvement effect on soil pH is T4 > T5 > T3 > T6 > T1 > T2, with particularly significant effects during the fruiting and ending stages.

Fig. 1



The characteristics of pH changes in 0–20 cm (**a**) and 20–40 cm (**b**) soil layers under different treatments during the whole growth period of tomato. *Note*: Different lowercase letters indicate significant difference of the same soil layer in

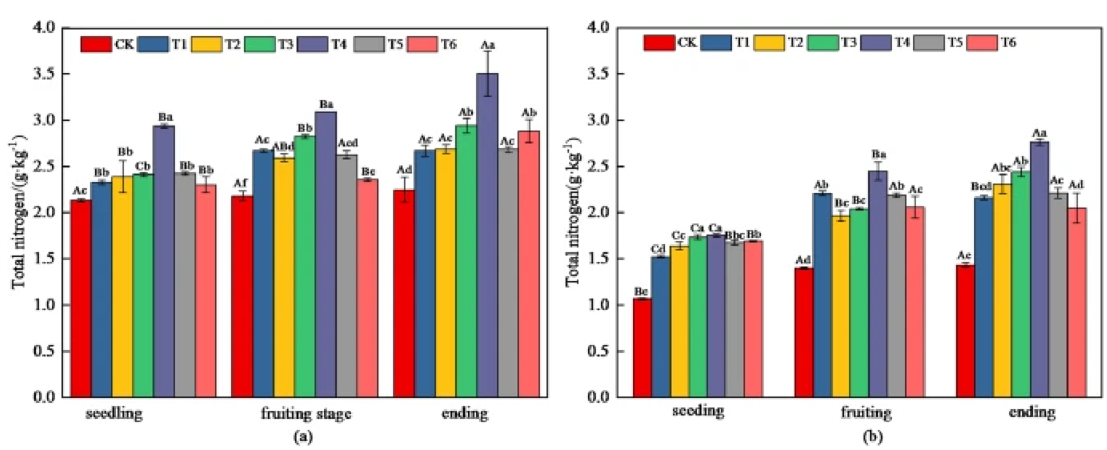
Impacts on the bulk density of facility soil

Table 3 presents the effects of diverse application dosage on soil bulk density within a facility agricultural setting. Understanding these impacts is crucial as soil bulk density is a fundamental parameter that significantly influences soil porosity, aeration, water-holding capacity, and root penetration, all of which are essential for plant growth and productivity. At the seedling stage, all treatment groups exhibited the ability to reduce soil bulk density. Notably, the T5 and T6 treatments demonstrated a marked deviation from the blank control. In the 0–20 cm soil layer, the T5 and T6 treatments achieved a reduction in soil bulk density by 15.72% and 10.06% respectively ($P < 0.05$). In the 20–40 cm soil layer, both T5 and T6 treatments led to a 10.32% decrease. This early-stage reduction in bulk density can be attributed to the physical and chemical alterations induced by the applied substances. For instance, the substances might have promoted the aggregation of soil particles, created larger pore spaces and thus reduced the overall density. During the fruiting stage, all treatments continued to exert a reducing influence on soil bulk density. The T4, T5, and T6 treatments were particularly prominent. In the 0–20 cm soil layer, the bulk density decreased by 9.27–10.60%, while in the 20–40 cm layer, it dropped by 7.19–10.32%. As plants enter the fruiting stage, their nutrient and water demand increase. The reduction in soil bulk density in these treatments likely enhanced the soil's ability to supply these resources, as a lower bulk density is associated with improved water infiltration and nutrient diffusion rates. At the ending stage, the efficacy of each treatment in improving the surface soil (0–20 cm) bulk density surpassed that of the deep-soil (20–40 cm). In the 0–20 cm layer, each treatment significantly decreased the soil bulk density, with a reduction range of 7.55–11.32. In the 20–40 cm soil layer, treatments T2, T3 and T4 showed distinct effects, with the T4 treatment achieving the highest reduction rate of 5.66%. The differential effect between surface and deep-soil could be due to the differential distribution of root systems and the degree of interaction between the applied substances and the soil matrix at different depths. Surface soil is more directly affected by the applied materials and root exudates, leading to more pronounced changes. Over the entire growth period, each treatment effectively reduced the soil bulk density of the 0–40 cm soil layer, with reduction rates of 6.09%, 6.30%, 6.73%, 8.55%, 9.83%, and 8.65%. The overall improvement effect followed the order T5 > T6 > T4 > T3 > T2 > T1. This order reflects the differential potency of the application dosages in modifying the soil structure. Higher-dosage treatments (T5 and T6) likely provided a more substantial quantity of the active components that contributed to soil particle rearrangement and pore-space creation, resulting in a more significant reduction in bulk density. In conclusion, the application of different dosages had a profound and consistent impact on reducing soil bulk density throughout the plant growth cycle, with implications for optimizing soil conditions for enhanced crop growth in facility agriculture.

Table 3 The characteristics of soil bulk density changes in 0–20 cm (a) and 20–40 cm (b) soil layers under different treatments during the whole growth period of tomato.

the facility. An in-depth analysis of the data reveals complex and significant trends throughout the growth cycle of the plants. During the seedling stage, all treatment groups exhibited a notable augmentation in the total nitrogen content of the soil, with a statistically significant difference when compared to the control group (CK). In the 0–20 cm soil layer, the enhancement range of the total nitrogen content spanned from 7.97–37.66%, while in the 20–40 cm soil layer, it ranged from 42.61%to 64.28%. This early-stage increase in total nitrogen can be attributed to multiple factors. Firstly, the additives in the treatments might have provided a direct source of nitrogen-containing compounds. For example, certain organic amendments could have been rich in nitrogen-based substances such as proteins or amino-acids, which were gradually mineralized and released into the soil. Secondly, the introduction of various materials might have altered the soil's microbial community structure. Microorganisms play a pivotal role in nitrogen cycling, and the changes in their abundance and activity could have facilitated nitrogen fixation, ammonification, or nitrification processes, thereby increasing the available nitrogen in the soil. As the plants entered the fruiting stage, the upward trend in total nitrogen content persisted. In the 0–20 cm soil layer, each treatment led to an increase in total nitrogen content ranging from 8.11 to 41.74%, and in the 20–40 cm soil layer, the increase was between 40.75% and 75.23%. At this stage, the continuous consumption of nitrogen by the growing plants, which have higher nutrient demands for fruit development, might have triggered a compensatory mechanism in the soil. The soil-plant-microbial system interacted in a way that the treatments further promoted the mobilization of nitrogen reserves. Additionally, the decomposition of the applied materials might have continued at a relatively stable rate, continuously supplying nitrogen to the soil-plant system. At the ending stage of the growth cycle, the improvements in total nitrogen content became even more pronounced. In the 0–20 cm soil layer, each treatment enhanced the total nitrogen content by 18.84–56.08%, and the total nitrogen content in the 20–40 cm soil layer increased by 43.10–92.59% ($P < 0.05$). The cumulative effect of the treatments over time was evident. The long-term decomposition and transformation of the applied substances, along with the continuous cycling of nitrogen within the soil ecosystem, contributed to this substantial increase.

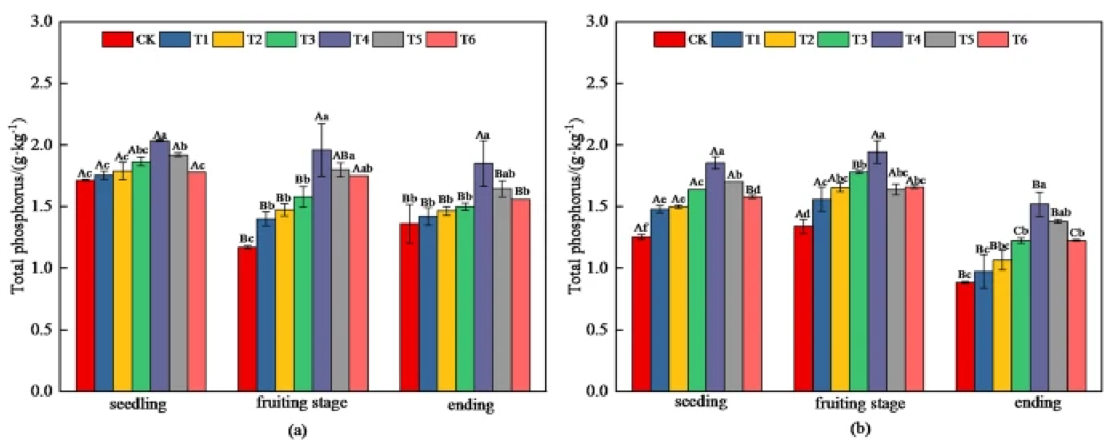
Fig. 2



Impacts on total phosphorus in facility soil

The influence of different application dosages of biochar, plant ash, and EM bacteria on soil total phosphorus is depicted in Fig. 3. This phenomenon is not merely a surface-level change but is deeply rooted in the complex interactions within the soil ecosystem. As the application amount of biochar, plant ash and EM bacteria, there are notable improvements in the total phosphorus content in both the 0–20 cm and 20–40 cm soil layers during the seedling, fruiting, and ending stage($P < 0.05$). The underlying reason lies in the unique properties of these amendments. Biochar, for instance, has a high surface-area-to-volume ratio, which can adsorb and retain phosphorus, reducing its leaching loss and making it more available in the soil. Plant ash is rich in various minerals, including phosphorus-containing compounds, which directly contribute to the increase in soil phosphorus. EM bacteria can enhance the decomposition of organic matter in the soil, releasing bound phosphorus and promoting its cycling within the soil-plant system. Among all treatments, T4 exerted the most pronounced effect on increasing soil total phosphorus. During the seedling stage, the total phosphorus content in the 0–20 cm soil layer increased by 2.33–18.66%, and in the 20–40 cm soil layer, the increase was significant ($P < 0.05$), ranging from 17.93–47.81%. At the fruiting stage, the total phosphorus content in the 0–20 cm soil layer rose by 19.66–67.52%, while in the 20–40 cm soil layer, it increased by 16.42–45.15%. At the ending stage, the total phosphorus content in the 0–20 cm soil layer increased by 4.41–36.03%, and in the 20–40 cm soil layer, it increased by 10.17–71.75%. Throughout the entire growth period, compared to the control (CK), the total phosphorus content of 0–40 cm soil in each treatment increased on average by 11.82%, 16.92%, 26.00%, 47.82%, 33.42%, and 26.04%. The order of the improvement effect was T4 > T5 > T6 > T3 > T2 > T1. This order indicates that the combination and dosage in treatment T4 were most effective in promoting the increase of soil total phosphorus, which may be attributed to the optimal synergy among biochar, plant ash, and EM bacteria in this treatment, maximizing their individual and combined functions in phosphorus regulation within the soil environment.

Fig. 3



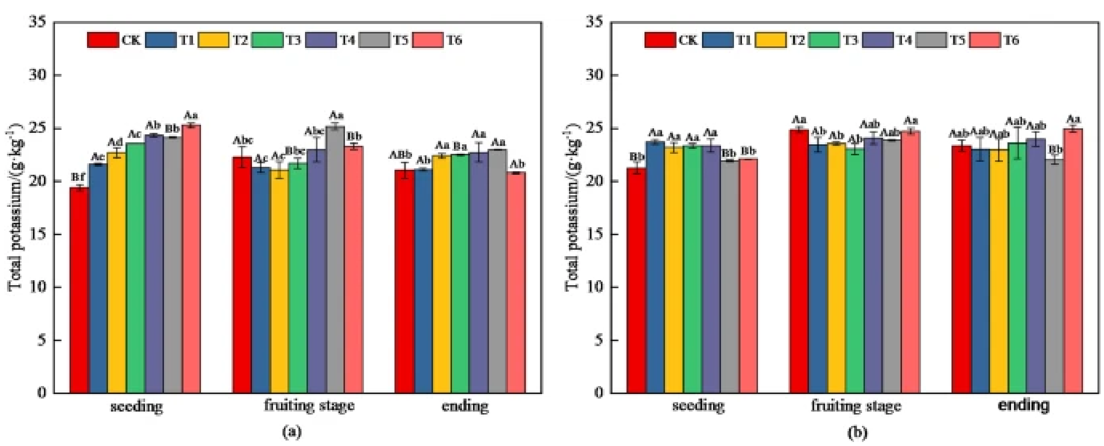
Impacts on total potassium in facility soil

The influence of different application dosages on the total potassium content in the soil of facilities is depicted in Fig. 4. During the seedling stage, in the 0–20 cm soil layer, all treatments led to an increase in total potassium content, ranging from 11.31 to 25.30%. In the 20–40 cm soil layer, each treatment resulted in an increase within the range of 8.98–11.37%, and these increases were statistically significant ($P < 0.05$). This initial increase can be attributed to the immediate release of potassium from the applied amendments, such as plant ash. The high solubility of potassium compounds in plant ash, mainly potassium carbonate, potassium sulfate, and potassium chloride (with potassium carbonate being the dominant form, accounting for over 90% of the potassium in plant ash), allows for rapid dissolution in soil water, making potassium readily available in the upper soil layers. At the fruiting stage, among the treatments, only the T5 treatment showed a significant increase (13.02%, $P<0.05$) in the total potassium content in the 0–20 cm soil layer. All treatments had no statistically significant effect on the total potassium content in the 20–40 cm soil layer ($P<0.05$). The limited impact on the deeper soil layer might be due to the relatively shallow penetration of water-soluble potassium in the soil. As plants grow, their root systems expand, and the competition for nutrients increases. The fact that only T5 had an effect in the 0–20 cm layer could be related to the specific dosage or composition of the amendment in T5, which provided a more sustained release of potassium compared to other treatments at this stage. At the ending stage, in the 0–20 cm soil layer, the T2, T3, T4, and T5 treatments showed increases in total potassium content of 6.41%, 6.91%, 8.00%, and 9.12% respectively, respectively, with significantly differences from the control (CK) ($P < 0.05$). In the 20–40 cm soil layer, there was no significant difference between each treatment and the CK ($P < 0.05$). This further indicates that the influence of the applied amendments on potassium content is mainly concentrated in the upper soil layer. The continuous but relatively smaller increase in the upper layer may be a result of the residual potassium from the previous stages and the slow-release properties of some potassium-containing components in the amendments. When considering the entire growth stage, compared to the control (CK), each treatment increased the soil total potassium content in the 0–40 cm soil layer on average by 1.44%, 2.74%, 4.17%, 6.99%, 5.97%, and 6.74%, respectively. The order of the overall improvement effect was T4 > T6 > T5 > T3 > T2 > T1. This overall trend reflects the cumulative effects of the amendments throughout the growth cycle, taking into account factors such as the rate of potassium release, plant uptake, and leaching losses. Plant ash, a rich source of potassium, serves as a beneficial natural potash fertilizer. The high water-solubility of its potassium compounds, as mentioned earlier, is a double-edged sword. On one hand, it allows for quick availability of potassium for plants, especially during the early growth stages when the demand for nutrients is high. This is why all treatments significantly increased the total potassium content in the 0–20 cm soil layer during the seedling stage. On the other hand, the high solubility makes it difficult for potassium to be retained in the soil. In sandy soils, where water infiltration is rapid, the potassium is easily washed away with water and does not penetrate deeply. As plants grow, they rapidly absorb and utilize the available potassium, fulfilling the role of a potash fertilizer. This dynamic process is consistent with the findings of this study.

direct supply of potassium in plant ash, while biochar mainly improves soil structure and cation-exchange capacity, and EM bacteria enhance soil biological activity rather than directly supplying potassium. The unique chemical composition of plant ash, with its high-solubility potassium compounds, gives it an edge in increasing soil total potassium content, especially in the short-to medium-term. In conclusion, the application of different treatments, especially those containing plant ash, has a significant impact on the total potassium content in the soil of facilities, with complex temporal and spatial variations influenced by the chemical properties of the amendments and the growth stage of the plants.

More than 90% of the potassium in plant ash exists in the form of potassium carbonate, potassium sulfate, and potassium chloride, predominantly as potassium carbonate. These three forms of potassium compounds are highly water-soluble, enabling them to act promptly and be absorbed and utilized by plants. During the seedling stage, all treatment significantly increased the total potassium content in the 0–20 cm soil layer. However, due to the high-water solubility of potassium compounds in plant ash, the potassium was difficult to retain it in the soil, and it did not penetrate deeply into the sandy soil with water. As the plants grew, the potassium was rapidly absorbed and utilized, thus fulfilling the role of a potash fertilizer, which is consistent with the findings of this study. Furthermore, based on the results of this study, plant ash had a more pronounced effect on the soil total potassium content compared to other amendments biochar and EM bacteria.

Fig. 4

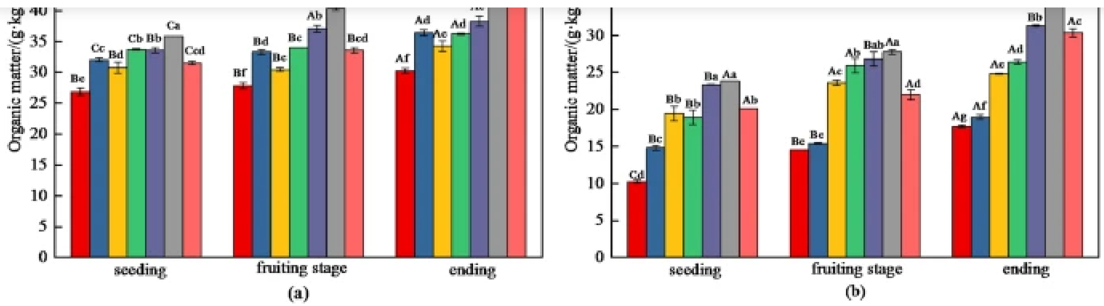


During the whole growth period, different treatments of 0–20 cm (**a**) and 20–40 cm (**b**) soil layer total potassium.

Impacts on facility soil organic matter

Figure 5 illustrates the effects of diverse application dosages on the organic matter content within the facility soil. During the seedling stage, all treatments exerted a significant influence, leading to an increase in the organic matter content across the 0–40 cm soil layer. Specifically, in the 0–20 cm soil layer, the increment substances, which are rich in organic components, are directly incorporated into the soil. Microbial activity is also stimulated at this stage. With the introduction of new organic materials, soil microbes find a fresh source of energy and nutrients. They begin to decompose these substances, breaking them down into simpler compounds that contribute to the increase in soil organic matter. Additionally, the relatively low nutrient demand of seedlings at this stage means that less organic matter is consumed for plant growth, allowing for a net accumulation in the soil. At the fruiting stage, in the 0–20 cm soil layer, each treatment brought about an increase in soil organic matter content ranging from 9.41 to 44.87% ($P < 0.05$), showing a significant difference compared to the control (CK). In the 20–40 cm soil layer, except for the T1 treatment, the treatments T2, T3, T4, T5 and T6 exhibited a remarkable increase in soil organic matter content, with an increment of 84.18– 90.53% ($P < 0.05$). As plants enter the fruiting stage, their nutrient requirements change. The root systems expand further into the deeper soil layers, and the rhizosphere environment becomes more complex. The treatments that show significant increases in the 20–40 cm layer might be due to the continuous decomposition of organic amendments in the deeper soil, along with the release of root exudates that can promote microbial activity in these layers. The lack of significant change in the T1 treatment could be related to its lower dosage or a less-effective composition of organic materials compared to the other treatments. At the end of each treatment, the soil organic matter content in the 0–40 cm soil layer was still significantly improved. In the 0–20 cm soil layer, the soil organic matter content increased by 13.27–62.12%, and in the 20–40 cm soil layer, it increased by 7.24–100.08%. This continuous increase throughout the growth cycle indicates the long-term effects of the applied treatments. The cumulative effect of the decomposition of organic materials over time, combined with the reduced leaching of organic matter in the later growth stages, contributes to this upward trend. As the plants approach maturity, the rate of organic matter decomposition may slow down, but the overall amount of organic matter in the soil has already been significantly increased due to the earlier activities. Over the entire growth period, compared to the CK, the soil organic matter content in the 0–40 cm soil layer of each treatment increased on average by 19.42%, 38.14%, 46.58%, 62.26%, 77.23%, and 49.10%. The overall improvement effect on soil organic matter followed the order T5 > T4 > T6 > T3 > T2 > T1. This ranking reflects the combined influence of various factors such as the quantity and quality of the applied organic materials, the efficiency of microbial decomposition, and the ability of the treatments to retain and accumulate organic matter in the soil. Treatments with higher-quality organic amendments, which are more easily decomposed by soil microbes and have a greater capacity to bind to soil particles, tend to show a more significant improvement in soil organic matter content. In summary, the application of different treatments has a profound impact on the organic matter content in facility soil, with complex temporal and spatial patterns that are influenced by factors such as the nature of the applied substances, microbial activity, and plant - soil interactions throughout the growth cycle of the plants.

Fig. 5

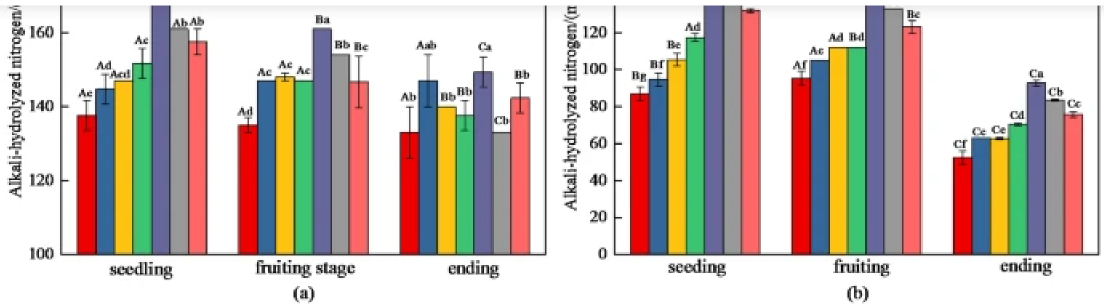


Different treatments of organic matter in 0–20 cm (**a**) and 20–40 cm (**b**) soil layers during the whole growth period of tomato.

Impacts alkali-hydrolyzed nitrogen in facility soils

The influence of diverse application dosages on the content of alkali-hydrolyzed nitrogen in facility soils is presented in Fig. 6. At the seedling stage, when compared to with the control group, each treatment demonstrated a significant augmentation in the alkali-hydrolyzed nitrogen content within the 0–40 cm soil layer. Specifically, in the 0–20 cm soil layer, the increase ranged from 5.09 to 22.04%, while in the 0–20 cm soil layer, it spanned from 8.81 to 83.91%. This significant increase can be attributed to the decomposition and mineralization of the applied substances, which release nitrogen-containing compounds into the soil. The root systems at the seedling stage have a relatively high demand for nitrogen to support rapid vegetative growth, and the applied substances provide a readily available source of this essential nutrient. During the fruiting stage, the 0–20 cm soil layer experienced an increase in alkali-hydrolyzed nitrogen content by 8.15–19.26%, and the 20–40 cm soil layer saw an increase of 10.14–50.00%. As the plants enter the fruiting stage, the demand for nitrogen further changes to support the development of fruits. The continuous presence and transformation of the applied substances in the soil contribute to maintaining and increasing the alkali-hydrolyzed nitrogen levels, meeting the plant's evolving nutrient requirements. At the end of the growth period, the 0–20 cm soil layer exhibited an increase in alkali-hydrolyzed nitrogen content of 0.16–12.29% and the 20–40 cm soil layer rose by 19.75–77.07%. Throughout the entire growth period, compared to the control (CK), the alkali-hydrolyzed nitrogen content of the 0–40 cm soil in each treatment was, on average, enhanced by 10.64%, 13.33%, 18.22%, 44.09%, 31.82%, and 25.90% respectively. Among all treatments, the T4 treatment was the most effective in enhancing the soil alkali-hydrolyzed nitrogen content in both the 0–20 cm and 20–40 cm soil layer, with the order of effectiveness being T4 > T5 > T6 > T3 > T2 > T1. The superior performance of T4 may be due to its unique chemical composition or physical properties that promote more efficient nitrogen release and retention in the soil, or a better match with the soil microbial community's nitrogen-cycling processes, which could be further investigated in future research to optimize soil fertility management in facility agriculture.

Fig. 6

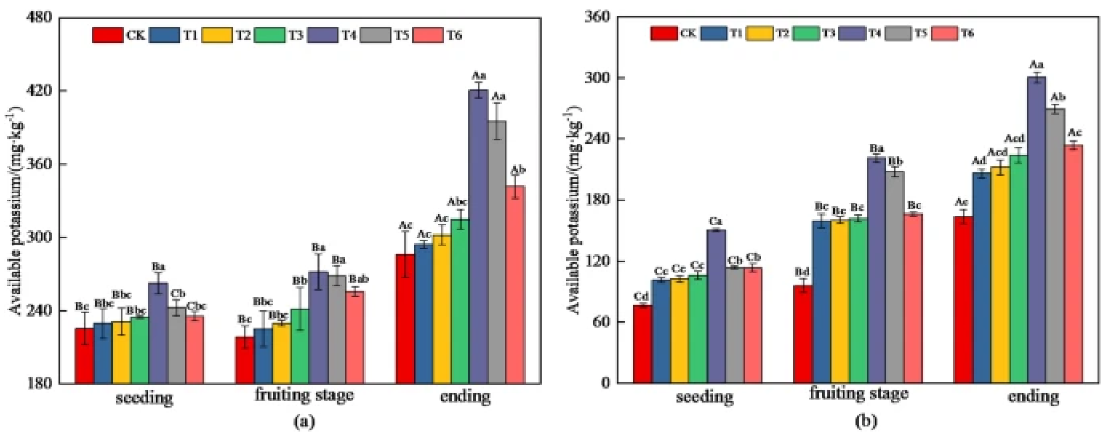


During the whole growth period, different treatments of 0–20 cm (**a**) and 20–40 cm (**b**) soil layer alkali-hydrolyzed nitrogen.

Impacts on available phosphorus in facility soil

Figure 7 illustrates the influence of varying application dosages on the content of available phosphorus in facility soil. This relationship is not a simple coincidence but rather reflects the complex interactions between the applied substances and the soil's nutrient cycling processes. In general, a significant proportional relationship was observed between the increase in soil available phosphorus and the dosages of each application amount in both the 0–20 cm soil layer and the 20–40 cm soil layer ($P < 0.05$). This indicates that the applied substances are directly contributing to the pool of available phosphorus in the soil. The chemical reactions between the applied materials and the soil matrix, such as dissolution and ion exchange, play crucial roles in releasing phosphorus into the soil solution, making it accessible to plants. Among the treatments, the T4 treatment demonstrated the most remarkable effect in enhancing the soil available phosphorus content. As the tomato growth period progressed towards its end, an increase in the content of available phosphorus was noted for each identical treatment. This upward trend can be attributed to several factors. Firstly, as the plants grow, their root exudates may modify the soil environment, promoting the solubilization of insoluble phosphorus compounds. Secondly, the decomposition of organic matter associated with the applied substances over time continues to release phosphorus, enriching the available phosphorus pool. At the seedling stage, the T4 treatment showed the best performance in increasing the soil available phosphorus content. Specifically, in the 0–20 cm soil layer, the available phosphorus content increased by 16.51%, and in the 20–40 cm soil layer, it rose by 96.64%. This substantial increase at the seedling stage is vital for the establishment and early growth of tomato plants, as phosphorus is essential for root development and energy transfer. During the fruiting stage, for the T4 treatment, the available phosphorus content in the 0–20 cm soil layer increased by 24.47%, and in the 20–40 cm soil layer, it significantly enhanced by 129.92% ($P < 0.05$). The higher demand for phosphorus during fruiting, to support fruit development and ripening, may drive the further mobilization and increase of available phosphorus in the soil. At the end of the growth period, the T4 treatment significantly elevated the available phosphorus content in the 0–20 cm soil layer by 47.15% and in the 20–40 cm soil layer by 83.51% ($P < 0.05$). Throughout the entire growth cycle, compared to the control (CK), each treatment increased the content followed the order of T4 > T5 > T6 > T3 > T2 > T1. The superior performance of T4 might be due to its unique chemical composition or physical properties that enable more efficient phosphorus release and retention in the soil, or it could have a more favorable interaction with the soil's biological and chemical components, which warrants further in-depth investigation to optimize phosphorus management in facility agriculture.

Fig. 7



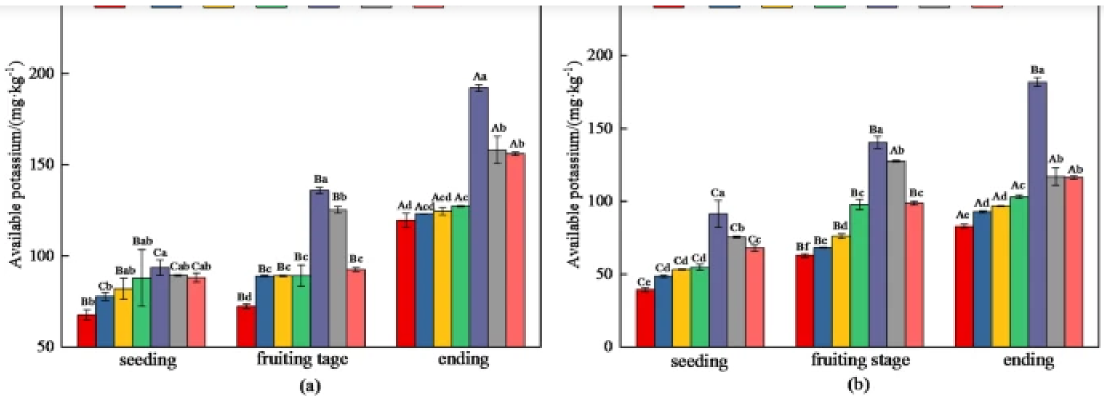
Available phosphorus in 0–20 cm (**a**) and 20–40 cm (**b**) soil layers under different treatments during the whole growth period.

Impacts on available potassium in facility soil

Figure 8 illustrates the effects of different application dosages on the available potassium content in facility soil. As the application dosages of biochar, plant ash, and EM bacteria increase in gradients, a statistically significant upward trend in available potassium content is evident in both the 0–20 cm and 20–40 cm soil layer ($P < 0.05$). This increase is underpinned by several complex mechanisms. Biochar, characterized by its high cation-exchange capacity, plays a crucial role in potassium retention. It adsorbs potassium ions, thereby reducing their leaching losses and ensuring a more consistent supply for plant uptake over an extended period. This property of biochar not only improves the efficiency of potassium utilization in the soil but also mitigates the environmental risks associated with potassium runoff. Plant ash, rich in potassium salts, serves as a direct source of potassium. Once applied to the soil, these salts dissolve, rapidly releasing potassium ions into the soil solution. This process enriches the soil's potassium pool, making it immediately available for plant roots to absorb. EM bacteria contribute to the potassium cycle through their interactions with soil minerals. By producing acids and chelating agents, they facilitate the release of potassium from its fixed forms in soil minerals. This microbial-mediated process is essential for enhancing the bioavailability of potassium, especially in soils where potassium is predominantly present in inaccessible forms.

soil layer and a substantial 132.88% increase in the 20–40 cm soil layer. At this early growth stage, plants have a burgeoning demand for potassium to support fundamental physiological processes such as osmoregulation, enzyme activation, and photosynthesis. The relatively large increase in the deeper soil layer (20–40 cm) can be attributed to the fact that the applied substances have a more significant impact on less-explored soil horizons, where the natural potassium availability is lower, and the root system is just beginning to explore for nutrients. At the fruiting stage, the T4 treatment increased the available potassium content in the 0–20 cm soil layer by 87.81%, and in the 20–40 cm soil layer by 123.39%. As plants enter the fruiting stage, their demand for potassium intensifies to support fruit development, including processes such as sugar translocation and fruit enlargement. The continuous decomposition and transformation of biochar, and plant ash, along with the metabolic activities of EM bacteria in the soil, contribute to the sustained increase in available potassium, meeting the elevated requirements of the plants. At the end-stage, the T4 treatment still exhibited a remarkable increase in available potassium. In the 0–20 cm soil layer, it increased by 60.64%, and in the 20–40 cm soil layer, it improved by 119.03%. Over the entire growth period, compared to the control (CK), the available potassium content of the 0–40 cm soil increased on average by 14.11%, 20.21%, 29.79%, 93.64%, 62.25%, and 43.06% respectively. The overall improvement effect of each treatment followed the order of T4 > T5 > T6 > T3 > T2 > T1. The superiority of the T4 treatment may be attributed to the optimal combination of biochar, plant ash, and EM bacteria amounts. This optimal combination likely created an ideal soil micro-environment, promoting more efficient potassium-releasing and-retaining processes. For example, it may have enhanced the activity of soil-borne microorganisms involved in the potassium cycle or optimized the soil's physical and chemical properties for potassium availability. Furthermore, within the same treatment and soil layer, the available potassium content in the soil increased as the tomatoes grew. This can be explained by the continuous decomposition of the applied substances over time, gradually releasing more potassium. Additionally, root-induced changes in the rhizosphere environment, such as the release of root exudates, can influence the mobilization of potassium from soil minerals and organic matter, contributing to the observed increase in available potassium content during the tomato growth cycle. These rhizosphere-mediated processes highlight the complex interplay between plants, soil, and microorganisms in nutrient cycling and availability.

It might have created an ideal micro-environment in the soil, promoting better potassium-releasing and-retaining processes, such as enhancing the activity of soil-borne microorganisms involved in potassium cycling or optimizing the physical and chemical properties of the soil for potassium availability. Furthermore, within the same treatment and soil layer, the content of available potassium in the soil demonstrated an increasing trend as the tomatoes grew. This can be explained by the continuous decomposition of the applied substances over time, which gradually releases more potassium. Additionally, the root-induced changes in the rhizosphere environment, such as the release of root exudates, can also influence the mobilization of potassium from soil minerals and organic matter, contributing to the observed increase in available potassium content during the growth cycle of tomatoes.



Available potassium of tomato in 0–20 cm (**a**) and 20–40 cm (**b**) soil layers under different treatments during the whole growth period.

Comprehensive impacts on soil fertility

Soil fertility, a crucial determinant of soil quality, encapsulates the fundamental physical, chemical, and biological properties of the soil. It serves as a cornerstone in agricultural research and sustainable land management, as it directly influences plant growth, crop yields, and overall ecosystem health. In this study, to comprehensively evaluate the soil improvement effect during the tomato growth period, several key parameters were selected: pH value, organic matter, total nitrogen, total phosphorus, total potassium, alkali-hydrolyzed nitrogen, available phosphorus available potassium, and available potassium. These parameters were used to calculate the soil comprehensive fertility index (*IFI*), providing a quantitative measure of soil fertility changes under different treatments. As presented in Table 4, during the transition from the seedling stage to the flowering and fruiting stage, the comprehensive soil fertility under the different gradients of biochar, plant ash and EM bacteria application dosages followed the order of T4 > T5 > T6 > T3 > T2 > T1. From the flowering and fruiting stage to the peak fruiting stage, the order was was T4 > T5 > T6 > T1 > T3 > T2. Over the entire tomato growth period, the comprehensive soil fertility ranking was T4 > T5 > T6 > T3 > T1 > T2. Upon closer examination, the overall trend of comprehensive soil fertility was observed to initially increase and then decreased with the increase of the fertilizer dosage gradient in each growth period. This non-linear relationship can be attributed to several underlying factors. In the initial stages of fertilizer application, the addition of biochar, plant ash, and EM bacteria enriches the soil with essential nutrients, improves soil structure, and enhances microbial activity. For example, biochar can increase soil porosity, which in turn improves water-holding capacity and aeration, creating a favorable environment for root growth and nutrient uptake. Plant ash provides a source of potassium and other minerals, while EM bacteria promote nutrient cycling and decomposition of organic matter. However, as the dosage of fertilizers increases beyond an optimal level, negative effects may emerge. Excessive application can lead to nutrient imbalances, such as an over-accumulation of certain elements that may be toxic to plants or disrupt the natural balance of the soil fertility. With a combination of plant ash at 3030 kg/hm², biochar at 6060 kg/hm², and EM bacteria at a ratio of 37.5:1, T4 achieved an optimal balance in nutrient supply, soil structure improvement, and microbial activity promotion. Therefore, the T4 treatment can be regarded as the optimal reference dosage, providing valuable insights for practical agricultural applications to enhance soil fertility and sustainable tomato cultivation.

Table 4 Effects of different treatments on the value of integrated fertility index in soils of facilities vegetable fields.

Discussion

Impacts of different application dosages on soil physical and chemical properties

Soil pH, a fundamental parameter determining soil acidity and alkalinity, plays a pivotal role in soil fertility[23]. The underlying mechanism is that it influences the solubility and availability of essential nutrients for plants. For instance, extreme acidic or alkaline conditions can precipitate certain nutrients, making them inaccessible to plant roots. Previous research has consistently shown that amendments such as biochar, plant ash, and EM bacteria can effectively modulate soil pH and nutrient content[9,20,24]. Biochar, an alkaline substance characterized by a complex porous structure and an array of functional groups like -OH and -COOH, exerts its influence through multiple pathways. Not only does it directly increase soil pH by virtue of its alkalinity, but it also adsorbs and exchanges cations, thereby regulating soil nutrient dynamics[25,26]. Plant ash, rich in carbonate, undergoes hydrolysis when it comes into contact with soil water. This chemical reaction produces hydroxide ions, which effectively counteract soil acidification[27]. As demonstrated by Yu[27], plant ash can raise the pH of acidified apple orchard soil by approximately 0.25, highlighting its significant role in ameliorating acidic soils. EM bacteria, on the other hand, contain diverse microorganisms whose metabolic activities buffer soil acidity and alkalinity. Through processes such as nitrification and denitrification, these microorganisms maintain a relatively stable pH environment in the soil[28].

In this study, a positive correlation was observed between the dosage of the biochar + plant ash + EM bacteria amendment and the improvement in facility soil pH. Each application gradient led to a 1.1– 24.0% increase in soil pH, effectively mitigating issues like soil acidification and continuous cropping obstacles. This finding aligns with the results of Fan[29], who reported that the combined application of biochar, EM bacteria-based organic fertilizer, and chemical fertilizer significantly enhanced soil pH and fertility indicators. The increase in pH can be attributed to the alkaline nature of biochar and plant ash, which directly neutralize soil acidity, while EM bacteria contribute to the overall stability of the soil's chemical environment, creating a more favorable condition for plant growth.

Soil bulk density, defined as the mass of soil per unit volume in its natural state, is intrinsically linked to soil texture, porosity, and structure. A lower soil bulk density is indicative of increased porosity, a looser soil enhance the friction between soil particles. This interaction results in the formation of a more compact yet porous soil structure. The porous nature of biochar and plant ash provides additional void spaces, while the EM bacteria-mediated aggregation of soil particles contributes to a more stable and well-structured soil matrix, effectively reducing soil bulk density[30]. In our study, each treatment reduced soil bulk density by 6.09–9.83%, significantly improving soil physical properties. This is in line with the research of Li[31], which showed a significant decrease in the soil bulk density of cotton and sugar beet fields at 0–10 cm and 10–20 cm depths with increasing biochar application. Blanco-Canqui[32] further elaborated that biochar reduces soil bulk density by interacting with soil minerals and reducing soil fill, thereby increasing porosity. The reduction in soil bulk density in our study represents a positive modification of the soil's physical structure, facilitating better root penetration and water-air exchange, which are crucial for the healthy growth of crops.

Impacts of different application dosages on facility soil nutrients

Soil organic matter is a cornerstone component of the soil solid phase and serves as a primary reservoir of plant nutrition. Total nitrogen, total phosphorus, and total potassium are key chemical indicators for evaluating soil quality, while alkali-hydrolyzed nitrogen, available phosphorus, and available potassium reflect the short-term nutrient-supplying capacity of the soil[19]. Favorable soil physical and chemical properties are preconditions for efficient plant root nutrient absorption, growth, and nutrient conversion. The complex interactions within the soil matrix, such as cation-exchange capacity and the activity of soil enzymes, are closely related to these properties.

Biochar promotes the accumulation of soil nutrients and enhances the absorption and storage of organic matter[33]. Zhu[34] found that biochar application increased the phosphorus content in agricultural soil, and different application amounts and cultivation times had significant effects on soil pH, organic matter, and available nitrogen content. The porous structure of biochar provides a large surface area for the adsorption of nutrients, and its recalcitrant nature helps to stabilize organic matter in the soil. Plant ash is rich in nitrogen, potassium, calcium, magnesium, and other available nutrients. Shi[35] demonstrated through a 3-year field corn experiment that the combined application of NP fertilizer and plant ash effectively increased the content of alkali-hydrolyzed nitrogen, available phosphorus, and available potassium in the soil. The nutrients in plant ash are readily released into the soil solution, contributing to the nutrient pool. EM bacteria, abundant in beneficial microorganisms, play a crucial role in balancing the beneficial microbial flora in facility agriculture soil and improving the soil microbial environment. Microorganisms in EM bacteria decompose soil organic matter into amino acids and carbohydrates, which are easily absorbed by plants, thereby increasing soil nitrogen content. Sun[36] showed in field experiments that EM bacteria increased soil nutrients and fertility, improving the soil's nutritional status and nutrient availability.

to the combined application optimized the availability of nitrogen, phosphorus, potassium, etc., significantly enhancing soil fertility. However, a “bottleneck effect” was observed in improving the effectiveness of soil nitrogen, phosphorus, and potassium. Specifically, when the combined application of biochar + EM bacteria + plant ash reached a certain level, the comprehensive soil fertility decreased. In this study, the T4 treatment had the most positive impact on comprehensive soil fertility, while treatments T5 and T6 showed a decline in fertility with increasing dosage. This phenomenon may be attributed to the high carbon content in biochar and plant ash. Excessive application can increase the soil C/N ratio, disrupting the balance and availability of soil nutrients[38]. A high C/N ratio can lead to a situation where microorganisms compete with plants for available nitrogen, as they require nitrogen for their own growth and metabolism during the decomposition of the high - carbon materials. This finding has profound implications for optimizing the application of these amendments in agricultural practices. It suggests that there exists an optimal dosage range to maximize soil fertility benefits while avoiding negative impacts on nutrient balance, highlighting the need for precise management in agricultural applications.

Overall, this study enriches the understanding of how the combined application of biochar, plant ash, and EM bacteria can modify soil physical and chemical properties and nutrient content in facility agriculture. The results offer valuable insights for sustainable soil management, aiming to improve soil quality, enhance crop productivity, and address issues related to soil degradation in intensive agricultural systems. Future research could focus on further optimizing the application ratios and long-term effects of these amendments to fully realize their potential in sustainable agriculture. Long-term studies are essential to understand the cumulative effects of these amendments on soil properties, as well as their impact on the long-term health and productivity of agricultural ecosystems.

Conclusion

This study demonstrates that the application of a compound amendment consisting of biochar, EM bacteria, and plant ash effectively improves the physical and chemical properties and soil nutrients of facility vegetable soil. During the tomato growth period, all treatments increased the soil pH in the 0–40 cm soil layer by 1.1–24.0% and reduced soil bulk density by 6.09–9.83%. This positively alleviated soil acidification, improved soil structure, and loosened the soil, enhancing its physical properties.

Simultaneously, soil nutrients in the 0–40 cm layer were optimized, with average increases in total nitrogen, total phosphorus, total potassium, organic matter, available nitrogen, available phosphorus, and available potassium by 8.0–56.1%, 2.1–53.9%, 0.2–30.3%, 19.42–77.23%, 0–22.0%, 3.0–47.2%, and 1.5–87.8% respectively. Overall, the combined application enhanced the comprehensive fertility of the facility soil. While increasing the application amount generally increased overall fertility, a “bottleneck effect” of first-increasing-then-decreasing was observed. Among the treatments, T4 (biochar 6060 kg/hm^2 + EM bacteria 37.5:1 + plant ash 3030 kg/hm^2) had the highest Integrated Fertility Index (*IFI*) and the most significant impact on soil fertility.

this compound amendment on soil quality and crop yields, as well as its potential environmental impacts. Additionally, investigating the interaction mechanisms between biochar, EM bacteria, and plant ash in the soil could provide a more in-depth understanding of their synergistic effects and help optimize amendment application strategies.

Data availability

Data is provided within the manuscript or supplementary information files. The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Change history

06 August 2025 A Correction to this paper has been published: https://doi.org/10.1038/s41598-025-14400-6

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M.S.: Data curation, Formal analysis, Validation, Software, Writing–original draft. S.F.: Conceptualisation, Methodology, Writing-review & editing, Supervision, Funding acquisition. N.Z.: Writing-review & editing.

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Ethics declarations

Competing interests

The authors declare no competing interests.

Additional information

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The original online version of this Article was revised: The original version of this Article contained a spelling error in the name of Shuanxi Fan, which was incorrectly given as Shuanxi X. Fan.

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Cite this article

Sun, M., Fan, S. & Zhang, N. Effects of biochar combined with the application of plant ash and effective microorganisms on the soil in the vegetable facility. *Sci Rep* **15**, 15824 (2025). https://doi.org/10.1038/s41598-025-98684-8

Received 14 November 2024

Accepted 14 April 2025

Published 06 May 2025

Version of record 06 May 2025

DOI https://doi.org/10.1038/s41598-025-98684-8

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Scientific Reports (*Sci Rep*) ISSN 2045-2322 (online)