RESEARCH ARTICLE

Impact of biochar on soil, plant growth, and quality in continuous faba bean cropping

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Received: August 3, 2024; **accepted:** December 13, 2024.

Continuous cropping causes the growth of faba beans to be slow, the fruits to be short and slender, prone to disease, with few grains and low yield, which has become a major obstacle to the sustainable development of faba beans in China and the world. Biochar has been widely applied in agricultural ecosystems to improve soil physicochemical properties. This study aimed to determine the effects of biochar on soil structure, growth, and faba bean quality under continuous cropping. The *in situ* remediation effects of different biochar amount on soil with continuous cropping were investigated. Biochar was prepared using rice husks as the raw material and applied in varying quantities to faba bean soil with continuous cropping. The effects of biochar on faba bean yield, disease index, rhizosphere soil physicochemical properties, and soil enzyme activities were examined. The biochar application rates were 0 t·667 m^{-2} as a control (CK), 10 t·667 m^{-2} (F1), 20 t·667 m^{-2} (F2), 30 t·667 m^{-2} (F3), and 40 t·667 m^{-2} (F4). The results showed that biochar effectively enhanced the soil pH, organic matter, humus, and the content of readily available nutrients. It reduced the incidence of faba bean chocolate spot and root rot diseases with the F2 treatment resulting in the lowest root rot incidence. The F2 treatment resulted in the best fresh pod length and yield followed by the F3 treatment. Incorporating biochar at various dosages significantly enhanced the activity of urease, catalase, invertase, and dehydrogenase enzymes in soil with continuous faba bean cropping, especially with the F2 and F3 treatments. Therefore, biochar could improve the physicochemical properties of soil, enhance enzyme activity, reduce the incidence of diseases in faba beans, and increase yield and quality. This study demonstrated that biochar had considerable potential for the *in situ* remediation of soils affected by continuous cropping, providing a theoretical basis and technical support for using biochar to address the challenges of continuous faba bean cropping.

Keywords: phenolic acid; biochar; faba beans; soil enzyme activity; continuous cropping.

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Introduction

Faba bean (*Vicia faba* L.) is a leguminous crop with excellent adaptability and high nitrogen-fixation efficiency, making it a multipurpose crop for grain, vegetables, fodder, and green manure. Faba bean has been cultivated in many countries worldwide, and its planting area has greatly expanded in China as part of agricultural restructuring [1, 2]. In recent years, the planting area of faba bean in Zhejiang Province has been constantly increasing with an annual planting area of approximately 13,300 ha. In 2023, the annual planting area of faba beans in Lishui was approximately 2.7 ha [3]. Continuous cropping of faba beans is common for economic benefits. However, faba beans are not tolerant of continuous cropping. This intense and continuous planting mode often leads to a decline in soil natural ecological regulation functions, limits plant growth and development, and results in weakened faba bean vigor and a substantial decline in yield. Under continuous cropping conditions, the allelochemicals secreted by the root system of faba beans, especially phenolic acids, accumulate continuously, which exacerbates the deterioration of the rhizosphere microenvironment and suppresses plant growth. Therefore, developing efficient technologies to alleviate the accumulation of autotoxic phenolic acids in the soil and improve the rhizosphere soil microecological environment can mitigate the problem of continuous cropping obstacles.

Biochar is a type of biomass material characterized by its porosity and strong adsorption properties [4]. It is produced from crop residues through pyrolysis under limited oxygen conditions. When applied to the soil, biochar can increase soil porosity, enhance soil aeration, and adsorb toxic and harmful substances, thereby improving the soil environment [5, 6]. In apples, biochar can effectively improve the structure and function of microbial communities, improve soil quality [7-9], and alleviate the obstacles to continuous cropping [10]. Biochar can also address the challenges of continuous cropping for long cowpea and broad beans, improve soil physicochemical properties and enzyme activities, reduce morbidity, and improve both yield and quality [11, 12]. However, the effects and mechanisms of biochar on the removal of pollutants in soil considerably vary with different dosages. For example, a low dosage of biochar may have poor adsorption and degradation effects, whereas a high dosage may lead to excessive adsorption and fixation effects, resulting in resource wastage [13, 14]. The appropriate dosage of biochar is crucial in mitigating the challenges of continuous broad bean cropping. Moreover, determining the optimal dosage holds practical significance for improving soil conditions in farmland and overcoming the challenges associated with continuous cropping.

This study aimed to determine the effects of different dosages of biochar on the yield, disease index, and soil enzyme activity of faba bean, and further to clarify the mechanism by which biochar alleviated the challenges of continuous cropping, focusing on changes in the rhizosphere microecological environment. Rice husk biochar was selected as the soil amendment and four different dosages were tested to explore its effects on soil with severe continuous cropping of faba beans. The findings of this study might provide a theoretical basis and technical support for the use of biochar to address the limitations of continuous cropping.

Materials and methods

Materials for testing

The main faba bean variety, "Zhecan No. 1" bred by the Institute of Crop Breeding, Zhejiang Academy of Agricultural Sciences (Hangzhou, Zhejiang, China), was selected in this study. The study area was in Lishui, Zhejiang, China with a latitude of 28.39942 north and longitude of 119.80022 east. The area has a subtropical humid climate with the annual average sunshine duration of 1,712 to 1,825 h, an average temperature of 17.6°C, an extreme maximum temperature of 41.3°C, and an extreme minimum temperature of –7.5°C, an average annual precipitation of 1,392 to 1,600 mm, the average frost-free period of 180 to 280 days. The soil was red soil with a pH of 5.85, an organic matter content of 31.62 $g \cdot kg^{-1}$, an alkali-hydrolyzable nitrogen content of 58.52 $mg \cdot kg^{-1}$, an available phosphorus content of 21.78 mg $g \cdot kg^{-1}$, and an available potassium content of 36.74 $mg \cdot kg^{-1}$. The biochar used in the test was rice husk biochar carbonized at 450°C from Zhejiang Golden Boiler Co., Ltd. (Jinhua, Zhejiang, China) with a pH of 9.24, an organic carbon content of 284.38 $g \cdot kg^{-1}$, and a total nitrogen content of 2.35 $g \cdot kg^{-1}$.

Experimental design

A single factor field experiment was conducted between October 2021 and April 2022 with four different doses of biochar applications. The experiments were divided into 5 groups including control (CK) group with no biochar treatment, F1 group with 10 t·667 m^{-2} biochar treatment, F2 group with 20 t·667 m^{-2} biochar treatment, F3 group with 30 t·667 m^{-2} biochar treatment, and F4 group with 40 t·667 m^{-2} biochar treatment. Each treatment was replicated 3 times. A total of 15 plots with each plot covering an area of 45 m^2 was applied in this study. Before plowing, for every 667 m^2, 500 kg of Yinhai commercial organic fertilizer (Yinhai Biological Organic Fertilizer Factory, Jiaxing, Zhejiang, China) and 50 kg of Xiyang compound fertilizer (NPK 15:15:15) (Guizhou Xiyang Industrial Co., Ltd, Guiyang, Guizhou, China) were applied. The soil was plowed to a depth of 20 - 25 cm using a IWC40-95FQ-DI plowing machine (Weima Agricultural Machinery Co., Ltd., Chongqing, China). After leveling the land, a bed-making machine was used to form beds with a width of 1.2 m, a height of over 25 cm, and a trench width of 30 cm. The plots were arranged using a randomized block design. Two rows were planted on each bed surface, and each row was trenched to a depth of 20 cm. Biochar was applied to the strips and mixed evenly with the 0 - 20 cm soil layer. A silver-black perforated plastic film (Zibo Linzi Luyu Plastic Products Co., Ltd., Zibo, Shandong, China) was used to cover the soil with holes 10 cm in diameter, spaced 35 cm apart, and a row spacing of 60 cm. The seeds that were full, uniform in size, and disease-free were planted with one seed per hole at a depth of 4 - 5 cm at a seeding rate of 4 - 5 kg per 667 m^2. Conventional management practices were used for cultivation, open-field cultivation, and management.

Investigation of faba bean root rot and chocolate spot diseases

Three surveys were conducted during the faba bean branching, flowering, and maturity phases. In each plot, five points were randomly selected using the serpentine layout method. Three plants were examined at each point for a total of 15 surveyed plants. The occurrence of root rot and chocolate spot disease had been previously investigated. The disease index was surveyed and counted according to a five-level classification standard [15]. The incidence rate was then calculated as follows.

Incidence rate (%) = (number of diseased plants / total number of plants surveyed) × 100%

Measurement of faba bean yield and quality

Actual yield measurements were obtained during the maturity phase of the faba beans. In each plot, 15 faba bean plants were randomly harvested to measure fresh pod length, 100-seed weight, and fresh pod yield. The seeds were used for quality index assessments. The vitamin C content of faba bean seeds was extracted using an oxalic acid solution and titrated using a 2,6-dichloroindifol solution (LMAI Bio, Shanghai, China). The soluble sugar content of faba bean seeds was determined using the anthone colorimetric method in a boiling water bath. The soluble protein content of faba bean seeds was measured using the Coomassie Brilliant Blue G-250 (LMAI Bio, Shanghai, China) staining method [16].

Assessment of soil physicochemical properties

During the faba bean branching, flowering, and maturity phases, rhizosphere soil in 0 - 20 cm depth was collected using the root-shaking method. After extracting the intact root systems, the soil loosely attached to the roots was shaken and discarded. A small brush was used to gently brush the soil in close contact with the roots in a sampling bag. The collected soil was thoroughly mixed, air-dried, sieved, and set aside for further analysis. Soil pH was measured using a potentiometric method with a soil-to-water ratio of 2.5:1. Soil organic matter was determined using the potassium dichromate external heating method. Soil humus was extracted with an extractant containing sodium pyrophosphate and sodium hydroxide followed by potassium dichromate oxidation with external heating. Soil alkali-hydrolyzable nitrogen was determined using the diffusion method. Soil available phosphorus was measured using the molybdenum antimony colorimetric method with a 722 visible spectrophotometer (Tianjin Daman, Tianjin, China) after extraction with hydrochloric acid-ammonium fluoride solution. Soil available potassium was determined using an FP6410 flame photometer (Shanghai Jingke, Shanghai, China) after extraction with ammonium acetate solution [17].

Soil enzyme activity

Soil sucrase activity was measured through the 3,5-dinitro salicylic acid colorimetric method using Shimadzu UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan) with the enzyme activity being expressed as the amount of glucose produced per gram of soil per day in units of $mg \cdot g^{-1} \cdot d^{-1}$ [18]. Soil urease activity was determined using the indophenol blue colorimetric method [19]. The enzyme activity was expressed as the amount of ammonium nitrogen produced per gram of soil per day in units of $mg \cdot g^{-1} \cdot d^{-1}$. Soil catalase activity was measured using the potassium permanganate titration method and was determined as the consumed volume of 0.10 $mol \cdot L^{-1}$ $KMnO_4$ per 1.00 g of dry soil in 1 h in unit of $mL \cdot g^{-1} \cdot h^{-1}$ [20]. Soil dehydrogenase activity was determined using the triphenyl tetrazolium chloride reduction method with colorimetric determination at 485 nm using the Shimadzu UV-1800 spectrophotometer and was expressed as the amount of triphenyl formazan (TPF) produced per gram of soil per day in unit of $\mu g \cdot g^{-1} \cdot d^{-1}$ [21].

Data analysis

All statistical analyses were performed using Excel 2020 (Microsoft, Redmond, WA, USA). Correlation analyses were performed using SPSS 19.0 (IBM, Armonk, New York, USA). Data plots were generated using Origin 2022 (https://www.originlab.com/). The significance of differences among treatments was determined using analysis of variance (ANOVA).

Results

Effects of different biochar dosages on the incidence of root rot and chocolate spot diseases in faba beans

Compared to the control (CK) group, biochar application significantly reduced the incidence rates of chocolate spot and root rot diseases in faba beans (Figure 1). During the mature stage, the incidence rates of chocolate spot disease in the biochar treatment groups (F1, F2, F3, and F4) were reduced by 19.71, 29.03, 34.29, and 14.16%, respectively, compared to that of the CK group, while the incidence rates of root rot disease were reduced by 42.42, 75.76, 72.73, and 54.44%, respectively, compared to that of the CK group. During the different growth stages of faba beans, the incidence rate of chocolate spot disease was significantly different ($P < 0.05$) with the lowest incidence rate at the branching stage and the highest at the mature stage. The incidence of root rot disease was similar to that of chocolate spot disease and gradually increased with the extension of the faba bean growing period. However, for treatments using biochar, the incidence rate of root rot disease between the branching and flowering stages was not significantly different, while, for the control group, the incidence rate of root rot disease was significantly different across all three growth stages ($P < 0.05$). Differences were observed in the effects of different biochar dosages on the incidence rates of chocolate spot and root rot disease in faba beans ($P < 0.05$). F2 and F3 groups were more effective at reducing the incidence rates of both diseases than F1 and F4 groups. The F3 treatment resulted in the lowest incidence rate of chocolate spot disease, which was significantly different from that of the other treatments ($P < 0.05$). The F2 treatment yielded the lowest incidence rate of root rot disease, although there was no significant difference between the F2 and F3 treatments.

Effects of different biochar dosages on faba bean yield

Compared to the CK group, all treatments with different amounts of biochar significantly enhanced the length and yield of fresh faba bean pods (Figure 2). The F1, F2, F3, and F4 groups resulted in increases of 4.30, 6.48, 6.15, and 3.43%, respectively, in the fresh faba bean pod length compared to the CK group. Similarly, the

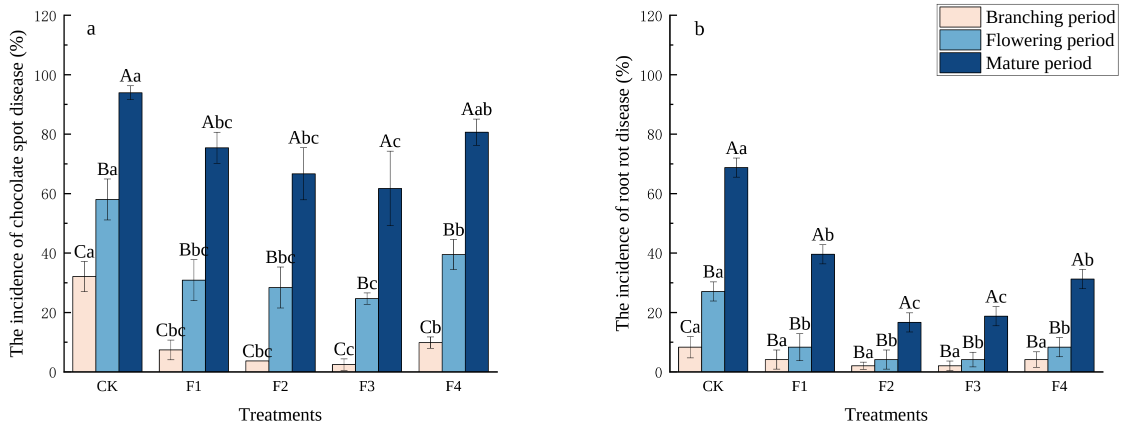

Figure 1. Incidence of red spot and root rot in faba beans under different treatments. Uppercase letters indicated significant differences in disease at different growth stages ($P < 0.05$). Lowercase letters indicated significant difference in the biochar application rate among different treatments ($P < 0.05$).

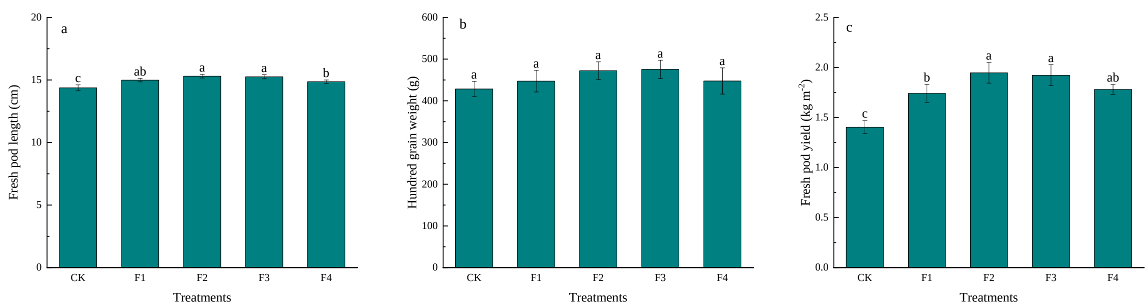

Figure 2. Fresh pod length, 100-grain weight, and fresh pod yield of faba beans under different treatments. Lowercase letters indicated significant differences between different treatments of biochar application rate ($P < 0.05$).

fresh faba bean pod yield increased by 24.02, 38.68, 36.98, and 26.86%, respectively. The differences between the four biochar treatments and the CK were significant ($P < 0.05$). The amount of biochar also affected the length and yield of fresh faba bean pods. As the amount of biochar increased, the length and quality of fresh faba bean pods initially exhibited an increasing trend followed by a decrease. The difference between the F2 and F3 groups was not significant. However, the differences in the length of fresh faba bean pods between the F4, F2, and F3 groups were significant ($P < 0.05$). The differences in the quality of fresh faba bean pods between the F1, F2, and F3 groups were also significant ($P < 0.05$). The F2 group exhibited the highest length and quality of fresh faba bean pods. Biochar application increased the hundred-seed weight of faba beans with the F1, F2, F3, and F4 treatments showing increases of 4.42, 10.24, 10.96, and 4.49%, respectively, compared to the CK group. However, the differences among the treatment groups were not significant. Overall, applying biochar could significantly improve the growth conditions of faba beans and increase yield with treatments F2 and F3 showing a pronounced effect.

Influence of different biochar dosages on faba bean quality

After biochar application, the vitamin C, soluble sugar, and soluble protein contents in faba beans were improved (Figure 3). Compared to the CK group, the application of biochar significantly enhanced the quality of faba beans in all treatments ($P < 0.05$). There were no significant

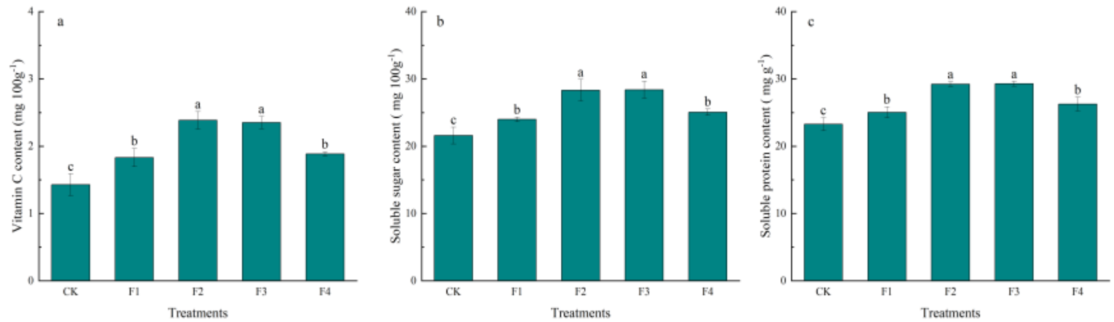

Figure 3. Effect of different treatments on the quality of faba beans. Lowercase letters indicated significant differences between different treatments of biochar application rates ($P < 0.05$).

differences between treatments F1 and F4 and between treatments F2 and F3. However, vitamin C, soluble sugar, and soluble protein contents were significantly higher in the F2 and F3 groups than those in the F1 and F4 groups.

Effects of different dosages of biochar on the physicochemical properties of rhizosphere soil in successive faba bean cropping

The application of different dosages of biochar significantly affected the soil physicochemical properties (Figure 4). Compared to the control (CK), the use of biochar increased soil pH, organic matter, humus, alkali-hydrolyzable nitrogen, available phosphorus, and readily available potassium. Throughout the different growth stages, as biochar dosage increased, the soil pH values of the treatments also increased (Figure 4a). During the branching stage, the soil pH of the biochar treatments (F1, F2, F3, F4) increased by 0.13, 0.69, 0.85, and 0.97 units, respectively, compared to CK. During the flowering stage, the soil pH of the biochar treatments (F1, F2, F3, F4) increased by 0.44, 1.01, 1.24, and 1.31 units, respectively, compared to CK. During the maturity stage, the soil pH of the biochar treatments (F1, F2, F3, F4) increased by 0.78, 1.20, 1.47, and 1.57 units, respectively, compared to CK. The results showed that, during different growth stages, the soil pH values of the treatments exhibited significant differences ($P < 0.05$). The contents of organic matter, humus, and readily available nutrients in the treatments with different biochar dosages peaked during the maturity stage. Compared to the control group, the application of biochar increased soil organic matter content by 51.44, 69.69, 69.80, and 66.30% for F1, F2, F3, and F4 treatments, respectively. F2 and F3 exhibited the most significant effects with no significant difference between them (Figure 4b). During the different growth stages, the differences in soil organic matter content were significant different ($P < 0.05$). During the maturation stage, biochar application increased the humus content by 23.06, 64.2, 58.97, and 33.79% compared to the control group. The differences among the treatments reached a significant level ($P < 0.05$) with the F2 treatment demonstrating the best effect (Figure 4c). For the F2 and F3 treatments, there were significant differences in soil humus content during the different growth stages. For the F1 treatment, there was no significant difference in soil humus content between the branching stage and the flowering stage, while the F4 treatment showed no significant difference in soil humus content between the flowering stage and the maturity stage. Biochar application during the maturation period increased the soil available nitrogen content by 58.52, 66.64, 65.42, and 52.20% compared to the CK, respectively, all of which were significantly higher than that of the CK group ($P < 0.05$) (Figure 4d). The F2 and F3 treatments showed the best effect with a significant difference compared to the other treatments ($P < 0.05$). However, there was no significant difference between them. When biochar was applied during the maturation phase, the available phosphorus content in each treatment increased by 142.77, 168.30, 185.32,

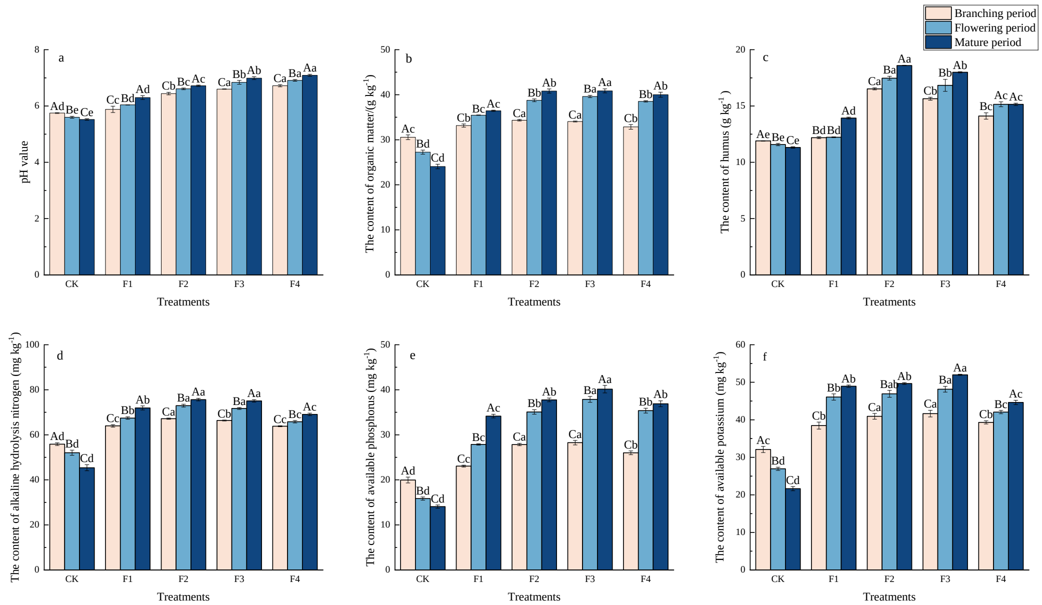

Figure 4. Changes in soil physicochemical properties under different treatments. Uppercase letters indicated significant differences in soil physicochemical properties at different growth stages ($P < 0.05$). Lowercase letters indicated significant difference between different treatments ($P < 0.05$).

and 162.20%, respectively, compared to CK (Figure 4e). The F3 treatment had the best effect, which was significantly more pronounced than that of the other treatments followed by the F2 treatment. However, the difference between F2 and F4 was not statistically significant. During the maturation period, the biochar application in each treatment increased the soil available potassium content by 126.07, 129.41, 140.06, and 106.12%, respectively, compared to CK (Figure 4f). However, the F3 treatment performed the best with the resulting increase being significantly higher than that observed in other treatments ($P < 0.05$). There was no significant difference in the soil available potassium content between the F1 and F2 groups. However, the soil available potassium contents in both groups were significantly higher than that in the F4 treatment ($P < 0.05$). During the different growth stages, the soil contents of alkali-hydrolyzable nitrogen, available phosphorus, and readily available potassium showed significant differences among the treatments ($P < 0.05$). With biochar application, each treatment reached its peak soil alkali-hydrolyzable nitrogen, available phosphorus, and readily available potassium contents during the maturity period for faba beans. The results indicated that soil biochar application under continuous faba bean cropping could significantly increase soil pH, organic matter, and the content of readily available nutrients, improving soil physical and chemical properties. The treatments of F2 and F3 groups exhibited the best effects.

Effects of different biochar dosages on enzyme activity in the rhizosphere soil of successively cropped faba beans

Biochar application at various dosages enhanced the activities of soil catalase, invertase, urease, and dehydrogenase (Figure 5). In the control group, the activities of soil catalase, invertase, urease, and dehydrogenase in the rhizosphere declined during the faba bean growth period, while the soil enzyme activities were the strongest during the flowering stage. As the faba beans grew and root exudates increased, the activity of soil enzymes decreased. Although the difference in catalase activity between the branching and flowering stages of faba beans was not significant, by the mature stage, the catalase activity significantly decreased. The activities of

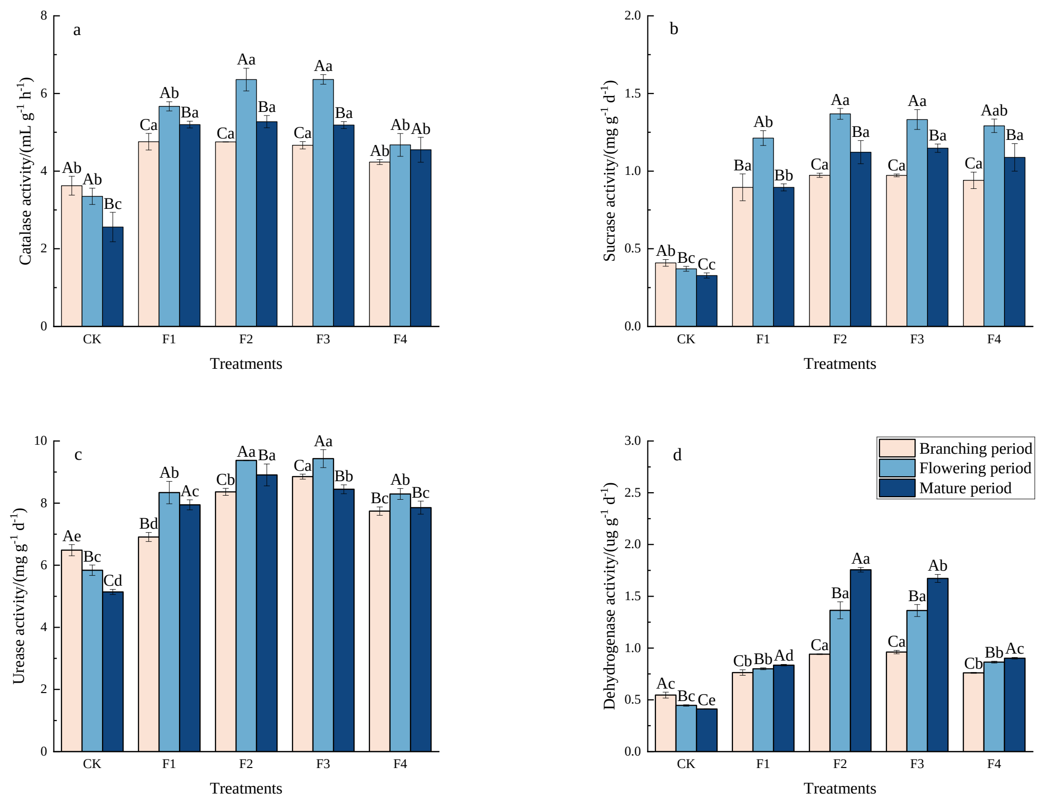

Figure 5. Changes in rhizosphere soil enzyme activity under different treatments. Uppercase letters indicated significant differences in rhizosphere soil enzyme activity between different growth stages ($P < 0.05$). Lowercase letters indicated significant difference between different treatments ($P < 0.05$).

soil invertase, urease, and dehydrogenase were significantly different ($P < 0.05$) across the various bean growth stages. In biochar treatments, the activities of catalase, invertase, and urease initially increased and then decreased. Peak activities of soil catalase, invertase, and urease were observed during the faba bean flowering stage. The F2 treatment resulted in the highest catalase and invertase activities, whereas the F3 treatment yielded the highest urease activity. The differences between the F2 and F3 treatments were not significant. The activity of soil dehydrogenase varied. With biochar application, it gradually increased during the growth period, reaching its highest activity at the mature stage of faba beans. The differences in dehydrogenase activity among the different dosages of biochar treatments were significant ($P < 0.05$). The F2 treatment exhibited the strongest soil dehydrogenase activity.

Correlation analysis of soil physicochemical properties, enzyme activities with faba bean yield, and quality

The correlations between the growth status, disease incidence, and quality of continuously cropped faba beans and the soil physicochemical properties and enzyme activities were examined (Figure 6). The faba bean growth status demonstrated a highly significant negative correlation with soil pH, humus content, and dehydrogenase activity ($P < 0.01$). There was a significant negative correlation with soil organic matter content, available phosphorus content, and the activities of soil invertase and urease ($P < 0.05$). The incidence of faba bean diseases and faba bean quality showed a highly significant positive correlation with soil pH, organic matter, humus, available phosphorus, available potassium, and invertase, urease, and dehydrogenase activities ($P < 0.01$). The results

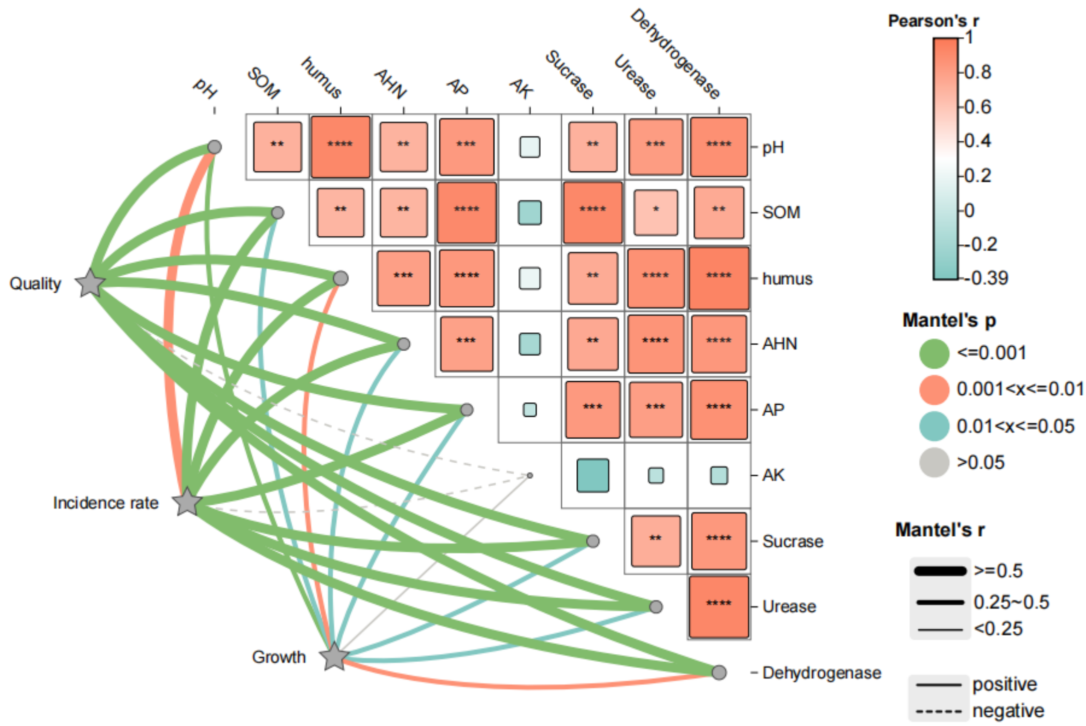

Figure 6. Correlation analysis of faba bean disease incidence, yield, and quality with soil physicochemical properties and enzyme activities.

indicated that, as the physicochemical properties of the continuous cropping soil and the conditions of enzyme activities gradually improved, the incidence of faba bean diseases significantly decreased.

Discussion

Effects of biochar on the disease incidence, yield, and quality of continuously cropped faba beans

The growth, yield, and quality of faba beans are influenced by a combination of factors. Continuous cropping leads to the accumulation of autotoxic substances in the soil, especially phenolic compounds. These compounds affect the growth of faba bean roots and, subsequently, the growth of the entire plant, while also reducing the quality of faba beans. Continuous cropping can also cause soil compaction, soil acidification, reduction of soil nutrients, and structural damage. All these factors hinder the normal growth and development of faba beans, further leading to a decrease in their yield and quality. The application of different amounts of biochar to continuously cropped faba bean soil can improve soil physicochemical properties, reduce the incidence of faba bean diseases, increase yield, and enhance quality. In this study, the incidence of chocolate spot disease in the biochar treatment groups (F1, F2, F3, and F4) decreased at maturity. Notably, the effect of different amounts of biochar on the incidence of chocolate spot disease and root rot in faba beans varied among the treatments. The incidence of chocolate spot disease was the lowest under the F3 treatment, while that of root rot was the lowest under the F2 treatment. In addition, the results indicated that the incidence of chocolate spot disease in faba beans was significantly negatively correlated with soil pH, other soil physicochemical properties, and enzyme activities. The incidence of root rot in faba beans was significantly and negatively correlated with all measured soil physicochemical properties and enzyme activities. These findings indicated that the application of biochar could significantly reduce the incidence of faba bean diseases as the soil environmental conditions being improved. A previous study reported that applying 40 t·hm^{-2} of biochar to tomato fields increased tomato yield by 51.6%, while applying 60 t·hm^{-2} increased tomato yield by 49.6% [22]. In this study, compared to the control group, the application of various biochar treatments in F1, F2, F3, and F4 groups increased the length of fresh faba bean pods, the weight of 100 faba beans, and the fresh pod yield, respectively, which suggested that the use of biochar could significantly improve the growth of faba bean plants and increase their yield. Although the effects of treatments F1 and F4 were comparable, those of treatments F2 and F3 were significant and did not differ significantly from each other, indicating that applying an excessively high proportion of biochar might reduce crop yield. Varying amounts of biochar were applied to the soil in this study. The results demonstrated that biochar significantly enhanced faba bean quality. The contents of vitamin C, soluble sugar, and soluble protein in faba beans from all biochar treatments were significantly higher than those in the CK group. Moreover, although the effect of different biochar amounts on the quality of faba beans varied, no difference between the F2 and F3 treatments was observed. Both treatments resulted in better quality beans than the F1 and F4 treatments. These results could be attributed to the improved growth of the faba bean root system due to the addition of rice husk biochar to the soil, which, in turn, could have promoted the growth of the aboveground stems and leaves, enhanced the photosynthesis rate, and facilitated the absorption, use, and transportation of nutrients within the plants, thereby improving quality. Guo *et al*. found that biochar increased corn yield, likely due to an increase in soil organic carbon, readily available phosphorus, potassium, and enzyme activity [23]. Agbna *et al*. reported that the application of biochar significantly increased the quality of tomatoes, which was associated with the effects of biochar in enhancing soil water retention and increasing readily available nitrogen, phosphorus, and potassium content [24]. Consistent with the previous studies, this research observed that the growth and quality of faba beans exhibited a strong and significant correlation with soil pH, organic matter, available phosphorus content, and the activities of invertase, urease, and dehydrogenase.

Impact of biochar on the physical and chemical properties of continuous cropping faba bean soil

Adding biochar to problematic soils can effectively improve the soil environment. This study demonstrated that the contents of organic matter, humus, and readily available nutrients peaked at maturity in treatments with different amounts of biomass charcoal. Compared to the CK, the organic matter contents in the soil treated with biochar increased with treatments F2 and F3 exhibiting the most significant effects despite no significant difference between them. The humus content also increased with the F2 treatment demonstrating the most potent effect. The content of alkali-hydrolyzable nitrogen increased as well with treatments F1 and F4 demonstrating comparable effects, although there were no significant differences between them. Treatments F2 and F3 also showed comparable effects with both having the highest increase in alkali-hydrolyzable nitrogen content but no significant difference between them. The available phosphorus content increased with treatment F3 demonstrating the best effect. This increase caused by treatment F3 was significantly higher than that observed with other treatments and followed by treatment F2 with no significant difference from treatment F4. The readily available potassium content increased with no significant difference between treatments F1 and F2, while treatment F3 was the best, which was significantly higher than the others. Treatment F4 had the relatively lowest improvement effect. Considering the overall impact of biomass charcoal application on the physical and chemical properties of phenolic acid-contaminated soil in continuous cropping faba beans, F2 and F3 treatments both showed favorable results. The findings of this study were similar to the results of Kunyan *et al*. [25] who found that biochar significantly improved the pH of acidic soils and increased the content of readily available nutrients. Biochar could enhance the retention capacity of soil for nitrogen and potassium, which, in turn, could improve crop nutrient use rates [26]. Ruihua *et al*. found that higher proportions of biochar application strongly immobilized soil nitrogen, leading to excessively high soil C/N ratios, which reduced microbial vitality and soil enzyme activity, further decreasing the content of available N, P, K, and other soil elements [27]. This previous report was consistent with the results of this study, where treatments F2 and F3 had comparable effects. However, the F4 treatment was less effective than the F2 and F3 treatments.

Impact of biochar on the enzyme activity of continuous cropped faba bean soil

Soil enzyme activity reflects the soil health status, promotes the cycling and transformation of soil nutrients, and directly affects crop growth and development. In this study, the activities of catalase, invertase, urease, and dehydrogenase in the rhizosphere soil of the CK group showed declining trends during the faba bean growth period. In the biochar treatments, the activities of catalase, invertase, and urease first increased and then decreased. The highest activity was observed during the flowering period. The F2 treatment exhibited the highest catalase and invertase activities followed by the F3 treatment. Moreover, the highest urease activity was observed in the F3 treatment group followed by the F2 treatment with no significant differences between treatments. Soil urease activity gradually increased during the growth period with the strongest activity in the F2 treatment followed by the F3 treatment, although there was no significant difference between the two groups. Biochar is rich in porous structure and surface area, which enables it to adsorb many enzymatic reaction substrates in the soil and increases the binding sites for soil enzymes, thereby enhancing soil enzyme activity [28]. Biochar can effectively promote soil moisture retention, adjust soil bulk density, and increase soil porosity, leading to increased soil enzyme activity [29]. Applying biochar to soil can boost soil carbon levels and regulate the water and nutrient balance system, providing suitable conditions and ample substrates for soil enzymatic reactions [30], which, in turn, enhances soil enzyme activity. Tu *et al*. reported that 1% biochar could significantly increase the activities of soil catalase and urease, while 5% biochar reduce enzyme activity, as a high proportion of biochar could harm soil microorganisms [31]. Biochar applied at 10, 20, and 30 t effectively increased the activities of catalase, invertase, urease, and dehydrogenase. In contrast, 40 t of biochar reduced the activities of all four enzymes compared to the 20 and 30 t applications. In this study, biochar application promoted soil enzyme activities with the 20 t and 30 t biochar treatments exhibiting the greatest improvement in soil enzyme activities, which suggested that the application of 20 - 30 t of biochar was the most appropriate method for continuous cropping of faba bean soil.

Conclusion

Among the various soil environmental factors, pH, organic matter, humus, and readily available nutrients are the key factors driving microbial community variability and regulating the incidence, yield, and quality of faba beans. The study showed that biochar could effectively increase the soil pH, organic matter, humus, and readily available nutrients, while the application of biochar reduced the incidence of faba bean chocolate spot and root rot diseases. Root rot is one of the most serious diseases in the cultivation of faba beans. The F2 treatment demonstrated the lowest incidence. Biochar also increased yield and quality of faba bean by increasing the contents of soluble sugars, vitamin C, and soluble proteins. The application of biochar at different rates significantly enhanced the activities of urease, catalase, invertase, and dehydrogenase in continuous cropping of faba bean soil, thus improving soil health quality. The F2 and F3 treatments were effective in enhancing enzyme activities. Considering the research results and economic benefit, the application of 20 t·hm^{-2} of biochar was recommended.

Acknowledgements

This research was funded by a Sub-project of the Lishui Public Welfare Project of China (Grant No. 2019GYX12).

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