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A Review: Progress in the Mitigation of Soil Continuous Cropping Obstacles by Biochar Application in Agricultural System

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Abstract

Under the dual pressure of agricultural economic development and limited land resources, the continuous cultivation in same area has been a mainstream pattern. The continuous cropping obstacle has seriously impaired the soil physicochemical properties and soil microflora, hindering the sustainable development of agriculture. Various strategies have been used to mitigate the negative effects caused by continuous cropping; however, they cannot be solved effectively. Recently, biochar, as a new type of soil conditioner, has been found to be able to utilize its special physicochemical properties and adsorption properties to improve soil quality conditions. Besides, biochar application is one of the effective methods to reduce the obstacles of soil continuous cropping. In this paper, we reviewed the causes of soil continuous cropping obstacles and their effects on soil and plant, and emphatically analyzed the regulatory role and potential limitations of biochar in alleviating soil continuous cropping obstacles. For example, the type of raw material, pyrolysis conditions of biochar and differences in soil types would yield different effects on the efficiency of biochar on soil continuous cropping obstacles mitigation, Furthermore, other influenced factors, such as the adsorption of biochar on root secretion, the interactions among plants, soils, and microorganisms, need to be investigated. This article provides theoretical support for the application of biochar in in alleviating soil continuous cropping obstacles.

Keywords: biochar; continuous cropping obstacle; soil properties; agriculture

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1. Introduction

Healthy soils play a key role in sustainable agriculture, ecosystems, and human health (Doran & Zeiss, 2000). For agricultural development, it not only provides plants with nutrients such as nitrogen, phosphorus, and potassium to promote normal growth and development but also maintains or improves water and air quality, which helps to enhance the quality and productivity of crops and increase their taste and nutritional value. From the ecological point of view, healthy soil, as a biological habitat, not only provides basic protection for the survival and reproduction of plants, animals, and soil microorganisms, but also promotes the decomposition of soil organic matter, increased fertility, and nutrient cycling, and finally maintains the micro-ecological balance of the soil. In addition, healthy soil has a positive effect on preventing excessive water loss, purifying groundwater, reducing soil erosion and infertility, and maintaining soil quality stability. Therefore, healthy soil is the basis for maintaining sustainable agricultural development and protecting the ecological environment and human health. Soil protection and sustainable land management should be attached importance to ensure the health and sustainable use of soil.

With the rapid growth of the population, crop production and food demand also increase. However, to meet human needs, excessive agricultural reclamation, irrational farming patterns, and excessive use of chemical fertilizers and pesticides have occurred frequently. According to statistics, the area of continuous cropping soil in China accounts for more than 10-20% of the total production area (Li & Yang, 2016). As a result, soil acidification, increased pests and diseases, nutrient imbalance, and changes in the structure of microbial communities have occurred, and the continuous cropping obstacle has become a primary problem.

Currently, the application of biochar is considered one of the effective methods to reduce the obstacles of continuous cropping in soil. Biochar has special adjustable properties such as high porosity and surface area, high pH, good stability, and high cation exchange capacity, which can enhance the physicochemical properties of soil (Brtnicky et al., 2021). Besides, it can improve soil fertility, porosity, water retention, and carbon storage capacity, reduce soil bulk density and acidity (Ding et al., 2016), as well as enable the deposition of potentially toxic metals in the soil, and improve soil structure. This provides a more favourable habitat for microorganisms to increase the effectiveness of plant nutrients (De Medeiros et al., 2021) and promote the growth and activity of microorganisms. Ultimately improving crop yield and quality (Bello et al., 2021), and mitigating soil continuous cropping obstacles.

2. Analysis of the Obstacles of Soil Continuous Cropping and Their Causes

2.1. Concept of Soil Continuous Cropping Obstacles

Continuous cropping has become a global trend that is prevalent in modern agricultural systems (Wu et al., 2020). It is widely present in crop cultivation and medicinal plant cultivation. Continuous cropping disorder refers to the phenomenon of growing the same species or family of crops on the same piece of land for several years in a row, and even with normal cultivation and management, low yields, low quality, and high levels of disease can occur.

Previous studies have found that continuous cropping can lead to several problems such as structural deterioration, an increase in pests and diseases, a decrease in enzyme activity, accumulation of autotoxic substances, and changes in microbial communities in the soil (Aller et al., 2018). In addition, continuous cropping also affects the physical and chemical properties of soil, especially pH and soil nutrients. In recent years, studies have shown that long-term continuous cropping will lead to a decline in overall soil quality and accumulation of soil-borne plant pathogens, thus jeopardizing production (Zhao et al., 2020). It has also been suggested that continuous cropping leads to nutrient accumulation, soil acidification, soil salinization, and loss of biodiversity (Sun et al., 2020).

2.2. Analysis of the Causes of Soil Continuous Cropping Obstacles

Soil continuous cropping obstacles are caused by a variety of factors. Currently, researchers generally believe that the main causes of continuous cropping obstacles include the following three aspects:

i. Deterioration of soil physicochemical properties, such as increased soil salinization and acidification, and soil nutrient imbalances (Wang et al., 2022).

Studies have shown that continuous cropping affects soil pH, soil nutrients, moisture, and other physicochemical properties. For example, as the number of years of continuous cropping increases, pH decreases significantly, and nutrient ratios become imbalanced. The reasons for this may be due to the overuse of chemical nitrogen fertilizers, high tillage intensity, biodegradation of plant residues, and the resulting accumulation of soil organic acids (Pervaiz et al., 2020). In addition, the selective absorption of nutrients in the soil by crops can lead to the accumulation of unnecessary elements and the shortage of needed elements, thus affecting the soil nutrient balance. In successive plantings of the same crop, fixed fertilizers are often applied, inhibiting the mineralization of carbon and nitrogen (Mahal et al., 2019), limiting the ability of material transformation and cycling, and weakening the nutrient-chelating ability. Therefore, it is easy to cause soil nutrient element ratio imbalance, nutrient imbalance, and other phenomena (Hussain et al., 2019). The long-term application of fertilizers and the accumulation of organic acids tend to make the pH value decline and lead to soil salinization and acidification, thereby aggravating the obstacle of soil continuous cropping (Liu et al., 2021). The soil will become more and more difficult to cultivate.

ii. The accumulation of allelochemicals secreted by plant roots and the intensification of soil-borne diseases.

During the growth and development of plants, the root system releases into the soil a kind of plant secondary metabolic compounds called allelochemicals (including phenols, terpenes, and organic acids, etc.), which are widely present in various tissues and organs (Ippolito et al., 2020). These allelopathic substances directly or indirectly affect their development and growth or that of other organisms in the vicinity, thus exacerbating the problem of soil continuous cropping obstacles.

Although there are also positive promotional effects of allelopathy, many studies have elaborated more on the inhibitory effects of allelopathic substances. Allelopathic substances exert their toxic effects and change the soil microhabitat environment, transforming the bacterial-dominant soil into pathogenic dominant. In addition, it not only affects the permeability of plant cell membranes, respiration, photosynthesis, and water uptake but also affects the process of plant cell division and ultrastructure, hormone activity and content, receptor enzyme activity, and gene expression (Cheng & Cheng, 2015). This causes great harm to plant production, such as quality reduction and yield reduction (Zhimin et al., 2022). There are great differences in the types of allelopathic substances secreted by different plants in the rhizosphere (Zhao et al., 2024).

Based on the existing literature, it is found that the previous studies on the separation, purification, identification, mechanism of action, and influence of allelochemicals have been relatively detailed. However, the research on the elimination of the effects of allelochemicals on plants to mitigate the obstacles of continuous cropping is very limited.

iii. Changes in the structure of soil microbial communities, such as the accumulation of harmful bacteria, the reduction of beneficial bacteria, the dominance of pathogenic microorganisms, and the frequent occurrence of pests and diseases (Chen et al., 2022).

The health of soil can be judged by monitoring the diversity and metabolic activity of rhizosphere soil microorganisms (Dong et al., 2016). Changes in soil microbial communities may affect soil fertility and stability. Continuous cropping will lead to changes in soil microbial abundance and population structure, disturbing the ecological stability of the soil microenvironment (Liu et al., 2020). The overall number of soil microorganisms decreases, and the diversity of bacteria decreases, while pathogenic microorganisms increase (Zhang et al., 2022), which will result in poor crop growth and significant increases in disease incidence (Zhang & Wang, 2010).

Zhang et al. (2022) found that long-term continuous cropping resulted in a decrease in the relative abundance of beneficial dominant phyla such as Actinobacteria, Acidobacteria, and Campylobacter greens, and an increase in the relative abundance of pathogenic genera such as Alternaria nee and Didymellaceae. In addition, some studies have reported that the number of bacteria and actinomycetes decreased by 37.22% and 43.68%, respectively, and the number of fungi increased by 106.64%, and the diversity and homogeneity of functional taxa communities was significantly reduced compared to the positive crop (Zhang, 2009). Similarly, Li et al. (2020) used a high-throughput sequencing technique to analyse the changes in bacterial population structure and diversity in cucumber rhizosphere soil samples in the greenhouse with different continuous cropping years. They found that with the extension of consecutive years, the relative abundance of most genera of bacteria showed a general trend of increasing and then decreasing.

It has been suggested that the accumulation of fungal viruses and harmful bacteria in the rhizosphere soil may kill plant cells or produce toxins that inhibit plant growth (Manici et al., 2017). Not coincidentally, Zhao et al. (2018) speculated based on their study that changes in microbial community structure during long-term continuous cropping of peanuts may be caused by the long-term effects of peanut residues or root secretions. Therefore, it is believed that allelochemicals will have a certain influence on the structural and potential functional changes of soil microbial communities and that long-term continuous cropping will lead to inhibition of crop growth and reduce crop yield.

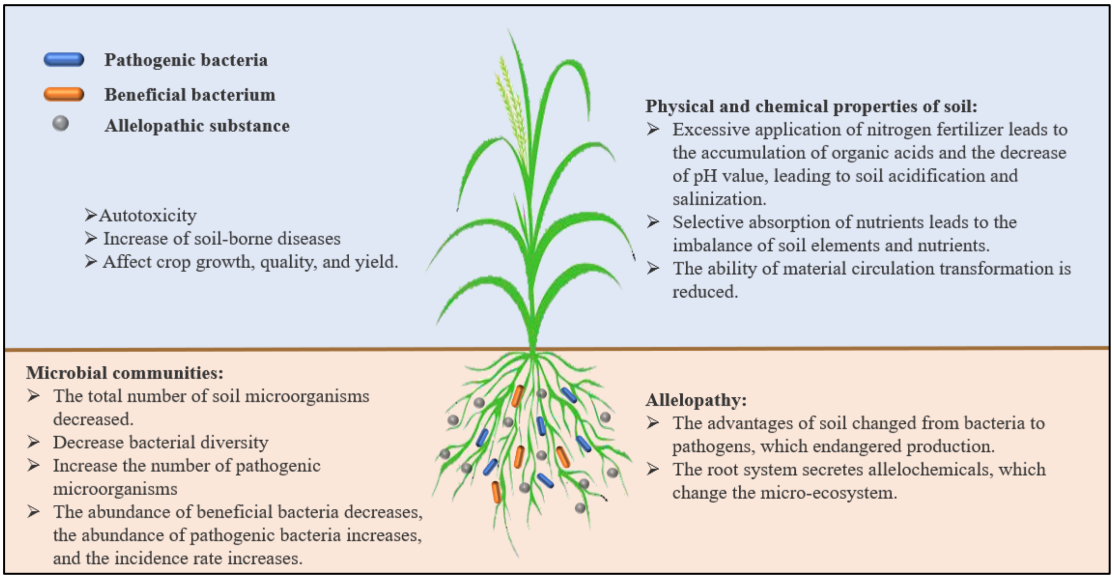

Figure 1. Mechanism of soil continuous cropping obstacle

3. Mechanism of Biochar Mitigating Soil Continuous Cropping Obstacle

At present, many strategies have been put forward to solve the problem of soil continuous cropping obstacles (Table 1), such as deep tilling treatments, the use of chemical fertilizer, the application of biologicals, and the selection of resistant varieties to deal with continuous cropping obstacles. Soil sterilization, crop rotation, and grafting techniques have also been proposed to mitigate soil continuous cropping obstacles. However, the above strategies may be harmful to the environment and lead to low-cost performance due to practical technical reasons, which makes the quality of the final products obtained may be unsatisfactory.

While the application of chemical fertilizers can provide transient relief from general crop pests and diseases, this method may lead to a significantly higher risk of soil acidification and salinization (Zhang et al., 2022). The development of resistant varieties takes a long time and is technically demanding. Breeding resistant varieties takes a long time and is technically demanding. Soil sterilization methods usually fail to address the root causes of the problem of crop barriers. The use of crop rotation methods can increase the number of soil aggregates and mitigate soil continuous cropping obstacles, but crop rotation stubble is closely linked, relatively demanding in terms of technology, and results in relatively low crop yields over the same period (McCollum et al., 2022). Intercropping management methods are relatively complex, and interspecific competition between different crops may have a certain inhibitory effect on crop productivity (Moore et al., 2022).

By introducing beneficial microorganisms into the soil, they can compete with harmful microorganisms for resources and space, antagonize the growth of harmful pathogens, and secrete substances that form a rhizosphere biological barrier to reduce the damage caused by pathogenic microorganisms or harmful bacteria (Kaari et al., 2023). Even though beneficial microorganisms have a positive effect on mitigating soil degradation caused by continuous cropping barriers, they often suffer from unstable application effects (Adesemoye & Kloepper, 2009). Therefore, exploring new integrated management approaches is the key to ultimately abating soil succession barriers.

Table 1. Traditional methods used for alleviation of the continuous cropping obstacles

Application strategy	Advantage	Disadvantage
Using chemical fertilizers	Alleviate general diseases and insect pests of crops.	1. Inhibit the growth of beneficial bacterial taxa. 2. It obviously increases the risk of soil acidification and salinization. 3. The susceptibility of crops to diseases increases and soil fertility decreases.
Selecting resistant varieties	1. Improvement of disease resistance in crops. 2. Improve crop yield and quality.	Long time required and high technical requirements.
Disinfecting soil	1. Eliminate the inhibitory effect of harmful microorganisms in soil on crop growth. 2. It has no effect on the physical and chemical properties of soil.	The problem of continuous cropping obstacles cannot be solved from the root cause.
Crop rotation	1. Enhance the activities of soil invertase, urease, catalase, and polyphenol oxidase. 2. Improve soil fertility, crop growth, yield, and quality. 3. Increase the number of soil aggregates and alleviate the obstacles of continuous cropping.	1. Crop rotation stubble is closely connected, so the technical requirements are relatively high. 2. At the same time, the crop yield is relatively low.
Row intercropping	1. Reduce soil ineffective transpiration. 2. Enhance the utilization and circulation of soil moisture by plants. 3. Enrich the rhizosphere microbial flora and reduce the occurrence of pests and diseases.	1. The method is complicated. 2. Interspecific competition among different crops may have a certain inhibitory effect on crop productivity.
Introducing beneficial microorganisms	1. Antagonize the growth of harmful bacteria. 2. Promote plant growth and control plant diseases.	The effect in combating crop diseases and insect pests is unstable.

3.1 Concept of Biochar

As an excellent soil improver, biochar is a kind of porous alkaline solid product rich in carbon produced by pyrolysis and carbonization of waste biomass under sub-high temperatures and anoxic conditions (Wang et al., 2021). It has been proven that biochar can not only be used to remove pollutants from the environment, reduce greenhouse gas emissions and energy production (Tan et al., 2017), but also improve soil fertility and plant growth (Dai et al., 2017; Xie et al., 2020). In addition, biochar can also be used to improve soil microbial habitat, directly affect microbial metabolism, promote soil biodiversity (Wang et al., 2020), and finally play a role in reducing soil continuous cropping obstacles (Dissanayake et al., 2020; You et al., 2018). Agricultural and forestry waste, animal manure, and other renewable organic matter can be used as biomass raw materials. To meet the need for biomass particles to be heated uniformly to obtain high-quality products, biochar production has changed the traditional mode, and with the support of modern innovative technology, slow pyrolysis, fast pyrolysis, gasification, roasting, and fast carbonization methods are used (Xie et al., 2022). According to

Alkharabsheh et al. (2021), the biochar produced by rapid pyrolysis has a high carbon content and is suitable to be used as a soil conditioner and soil carbon fixation too. However, Wang et al. (2020) found that biomass slowly pyrolyzed at about 400°C underwent a long period of "deep pyrolysis" at relatively mild temperatures, which facilitated heat transfer and carbon deposition reactions and resulted in higher quality and yield of biochar. The specific process and temperature used to prepare biochar should be reasonably selected according to the application.

3.2 Physicochemical Properties of Biochar

Various biological and chemical activities are often carried out on the surface of biochar, and these activities are related to the physicochemical properties of biochar. The characteristics of biochar mainly include element composition, the ratio of Oxygen/Carbon to Hydrogen/C porosity, specific surface area, pore size, pH value, water holding capacity, carbon content, and adsorption capacity. Biochar, as an organic fertilizer containing organic and plant nutrients, is generally composed of C (60-80%), H, O, Nitrogen (N), and small amounts of Phosphorus (P), Sulphur (S), Silicon (Si), Ferrum (Fe), Potassium (K), Calcium (Ca), and other elements (Kloss et al., 2012). The content of these elements increases with the increase in pyrolysis temperature, but their bioavailability decreases as they are contained in the highly aromatic structure of biochar (Yu et al., 2019). For example, in the case of slow pyrolysis of corn stalks, the exchangeable K of the biochar prepared at 400°C is more easily utilized by plant roots than that prepared at 500°C (Naeem et al., 2016). Therefore, to improve bioavailability and nutrient utilization, the low-temperature pyrolysis method can be chosen to prepare biochar. In the process of preparing biochar from biomass raw materials, proteins, cellulose, and other substances are pyrolyzed and carbonized to form internal and surface functional groups of biochar, mainly including hydroxy, Carboxyl, Ether, epoxy, amide, ester groups, and so on (Rajapaksha et al., 2016). Generally speaking, biochar is alkaline, with a pH value of 5.9-12.3 (Ahmad et al., 2014). The pH value of biochar increases as the pyrolysis temperature increases. Dai et al. found that, in most cases, biochar whose feedstock is manure has a higher alkalinity than biochar prepared from lignocellulose, compared to biochar prepared from the former (Dai et al., 2013; Enders et al., 2012).

The physicochemical properties of different biochars differ greatly from each other due to differences in pyrolysis temperature, type of feedstock, preparation process, etc. (Sun et al., 2014). Studies have shown that, within a certain range, as the pyrolysis and carbonization temperatures increase, the volatile substances decompose into gases, and the pore size, specific surface area, and microporous structure of biochar increase, and the microporous structure may also be damaged as the temperature exceeds the critical value (Chen et al., 2019). In addition, the increase in temperature will lead to an increase in the porosity of the biochar, a decrease in the O/C to H/C ratio, and a decrease in the number of oxygen-containing functional groups on the surface (Yu et al., 2019).

3.3 Effect of Biochar on Soil Physicochemical Properties

In recent years, numerous studies have shown that the application of biochar has effects on physical properties such as soil volume, soil structure, soil quality, water retention, porosity, hydraulic conductivity, carbon storage, and water content, as well as improving chemical properties such as soil pH and soil nutrient content. Therefore, biochar has a promising future for crop growth promotion and mitigating the application of soil continuous cropping barriers. Although biochar produced from toxic solid waste may have a potential risk of secondary contamination in specific cases, most biochar still brings beneficial effects to the soil as an amendment.

The experimental results of Muhammad and others showed that the combined application of biochar with N, P, and K fertilizers can significantly increase soil pH value, C content, fresh biomass, and dry biomass, and biochar treatment alone can also significantly increase soil pH and C content (Rafiq et al., 2020). Lu et al. showed that the biochar and plant residues increased soil carbon content by 45% and soil aggregation by 30% (Lu et al., 2020). Biochar acts as a carbon sequestering agent in the soil for a long period and improves soil physicochemical properties by utilizing its high carbon content and rich nutrients.

According to IUPAC standards, biochar pores can be categorized into macropores (> 50 nm), small pores (< 2 nm), and micropores (< 0.9 nm) (Sing, 1985). Saha et al. (2019) found that biochar contains interconnected macroscopic and microscopic porous networks by observing micrographs of biochar. The micropores with a particle size of 1-10μm keep the porous shape of biochar, which is helpful for biochar to keep the nutrients in the soil and improve the nutrient utilization rate. Wang et al. (2021) concluded that biochar has high cation exchange capacity and adsorption capacity, which can slow down the release of nutrients from the soil and likewise increase the nutrient utilization rate.

According to Panwar et al. (2019), biochar applied to soils with a depth of 10 cm can reduce the potential of denitrification, reduce nitrogen dioxide (N_2O) emissions, and reduce leaching of nitrogen into groundwater, thereby increasing water holding capacity, water utilization, and cation exchange capacity, while regulating soil acidity and promoting crop growth.

3.4 Effect of Biomass Charcoal on Soil Microorganisms

Soil microorganisms play an important role in controlling diseases, promoting crop growth, and improving nutrient utilization (Liu et al., 2018). Therefore, it is significant to improve the soil microbial environment to mitigate the soil continuous cropping obstacles. So far, many studies have shown that biochar treatment is beneficial to improving the structure of inter-root microbial communities, increasing the activity of soil enzymes, and maintaining the diversity of soil microorganisms (Ma et al., 2021; Wu et al., 2019). Also, it can improve soil enzyme activity, maintain soil microbial diversity, and increase soil microbial abundance. However, the effects of biochar amendments on microbial functional genes have yet to be investigated.

3.4.1 Soil Enzyme Activity

Biochar had a more significant effect on soil extracellular enzymes responsible for organic carbon degradation, phosphatase, sucrase, and other important nitrogen mineralization activities (Dai et al., 2021), but to a lesser extent on the activities of invertase and catalase (Chen et al., 2020). This effect varied depending on the nature of the biochar, soil type, and type of enzyme.

Oleszczuk et al. (2014) showed that when biomass charcoal was applied at 30 $t \cdot hm^{-2}$, it significantly increased the soil dehydrogenase, urease, protease, and alkaline phosphatase activities, while it did not have a significant effect on acid phosphatase activity; when biomass charcoal was applied at 45 $t \cdot hm^{-2}$, soil dehydrogenase, protease, and alkaline phosphatase activities began to decline. Later, Wang et al. (2021) found that biochar significantly increased the activities of urease and alkaline phosphatase by 23.1% and 25.4%, respectively, and that biochar produced under the conditions of pyrolysis temperatures of 350-550°C, pH > 10, and C/N < 50 was more effective than biochar produced under other pyrolysis conditions charcoal increased urease activity.

3.4.2 Soil Microbial Diversity

In general, biochar treatment of soil can provide habitat and nutrients for soil microorganisms to increase the biomass and diversity of microorganisms in the soil (Palansooriya et al., 2019). For example, the treatment of soil with biochar in which chili peppers had been continuously cultivated showed an increase in the activity and microbial diversity of Pseudomonas species, filamentous fungi, and Bacillus spp. in the soil (Gao et al., 2017). Karimi et al. (2020) applied 1% and 2% corn residue biochar to calcareous soil and counted the biomass of soil microorganisms, which showed an increase in biomass of soil microorganisms ranging from 20% to 124% compared to the control.

Generally, biochar application increases total soil microbial biomass as well as bacterial, actinomycete, and fungal biomass. However, contrary studies have found that the microbial composition and diversity after biochar treatment have not changed much compared with those before treatment (Ji et al., 2022). Liao et al. also observed that the composition and diversity of bacterial communities in the soil were very similar to those in the control group after applying biochar to cultivate crops for 21 days (Liao et al., 2021). Based on the physicochemical properties of biochar, it was speculated that microorganisms could not fully utilize the C, N, P, and other nutrients in biochar within a short period due to its stability and difficulty in decomposition

(Lehmann et al., 2011).

In addition, it has been reported that biochar-treated soil significantly increased the abundance and evenness of bacterial communities but had no significant effect on fungal communities (Wang et al., 2020). The reason for this is that the effect of biochar on the diversity of microorganisms, bacteria, and fungi in soil depends on the type of feedstock, pyrolysis temperature, and soil properties used for biochar production.

In terms of feedstock type, biomass charcoal with herbaceous feedstock showed a more significant increase in bacterial diversity compared to biochar with feedstock of manure, wood, etc. (Blanco-Canqui, 2017). In terms of soil properties, biochar applied to medium and coarse soils also had a significantly higher effect on bacterial diversity than fine soils (Palansooriya et al., 2019). For pyrolysis temperature, the application of biochar pyrolyzed at ≤700℃ to the soil significantly increased the total microbial and bacterial diversity, and only biochar produced by pyrolysis at ≤300℃ was also able to significantly increase the diversity of fungi in the soil. So, biochar produced under the above two pyrolysis temperature intervals had a significant increase in bacterial and actinomycetes diversity, whereas there was no significant effect on the diversity of fungi (Li et al., 2020). When the pyrolysis temperature was too high in the preparation of biochar, both bacterial and fungal diversity decreased with the increase in temperature (Abewa et al., 2013). Therefore, an appropriate application of biochar produced under suitable raw material and preparation conditions in soil can increase the activity and abundance of microorganisms and the obstacles of continuous cropping in soil.

3.4.3 Soil Microbial Community Structure

Biochar can increase microbial biomass and improve the community structure of soil microorganisms by providing an adequate carbon source for microorganisms in the soil.Some studies have shown that the application of biochar can change the microbial community structure of soil, but there is no highly significant effect. Yao found that the addition of biochar to karst soil increased the nutrient content of the soil, and improved the water-holding capacity, and the cation-exchange capacity (Yao et al., 2017). Therefore, by increasing the diversity of soil microorganisms, including bacteria and fungi, and inhibiting the growth and reproduction of harmful plant pathogens, biochar treatment indirectly changes the community structure of soil microorganisms, thereby improving the soil environment. (Yan et al., 2021). Jones et al. (2011) also observed a change in the microbial community structure in the soil due to a change in soil pH value after the application of biochar. However, the relationship between this change and the type of raw material and application rate of biochar has not been clarified.

The effects of biomass charcoal on soil microbial activity and community structure are complex and variable. The degree of influence is closely related to different biochar application rates, the time of biochar action in the soil, the raw materials for biochar preparation, the nature of the soil, and the conditions of biochar preparation (Khodadad et al., 2011). However, the mechanism of action remains to be further studied.

3.5 Impact of Biomass Charcoal on Crops

The application of biochar can change the structure of microbial communities, promote the production and growth of beneficial bacteria, and interfere with the growth of pathogenic bacteria, thus stimulating plant growth, improving plant disease resistance, preventing the occurrence of soil-borne diseases, and playing a positive role in improving the yield of continuous cropping plants (Liu et al., 2022).

3.5.1 Crop Quality and Yield

Many studies have reported that the application of biochar has great potential to improve crop quality and yield, especially in infertile soils where there are obstacles to continuous cropping, while it is ineffective for healthy soils, or even plays an inhibitory role (Van Zwieten et al., 2010). Jain et al. (2017) found that the application of biochar in acid mine soil helped to reduce the accumulation of toxic metals in plant tissues, improved soil fertility, and significantly increased the biomass of the medicinal plant, Portulaca oleracea. Also, have study concluded that the application of biochar usually helps to increase the water-holding capacity of the soil, and improve nutrient effectiveness and nutrient uptake by the plant, which in turn enhances the metabolic activity of the plant and increases the production of secondary metabolites. Nowadays, biochar has been proven to be widely used to improve soil problems in food crops such as wheat and rice, as well as vegetables, and to mitigate soil continuous cropping obstacles, thus improving their yield and quality (Wang et al., 2021).

3.5.2 Resistance to Soil-Borne Diseases

Continuous cropping obstacles lead to an increase in pathogenic microorganisms in the soil, which are highly susceptible to infecting roots or affecting the crop's ability to grow in the soil (Graber et al., 2014). Nowadays, the application of biochar amendments has been recognized as an effective treatment for the management of soilborne pathogens. Recent studies have shown that biochar can suppress soil diseases in cucumbers and tomatoes (Jaiswal et al., 2018). Chen et al., (2020) used biochar to treat soil and found that the incidence and disease index of green wilt was significantly lower than that of the control in a controlled experiment. Among the groups of concentration gradient treatments, the lowest disease index and incidence were found in the application of 15t·ha^{-1} biochar, with the incidence and severity of the disease being reduced by 58.72% and 69.81%, respectively, compared with the control. It can be inferred that biochar amendments have potential inhibitory effects on green wilt, with 15 t·ha^{-1} biochar being the most effective, followed by 7.5 t·ha^{-1} and 30 t·ha^{-1}.

Khalif et al. (2015) investigated the relationship between biochar soil amendment and tomato resistance to wilt and root rot and found that biochar application increased plant resistance to Fusarium acnes and Rhizoctonia solan, resulting in significant reductions in incidence and wilt and root rot severity, with incidence reduced by 85% and 80%, and disease severity reduced by 84% and 80%, respectively. In summary, biochar has significant positive effects in increasing plant resistance to soil-borne diseases and can be used as a good strategy for disease control and sustainable crop production.

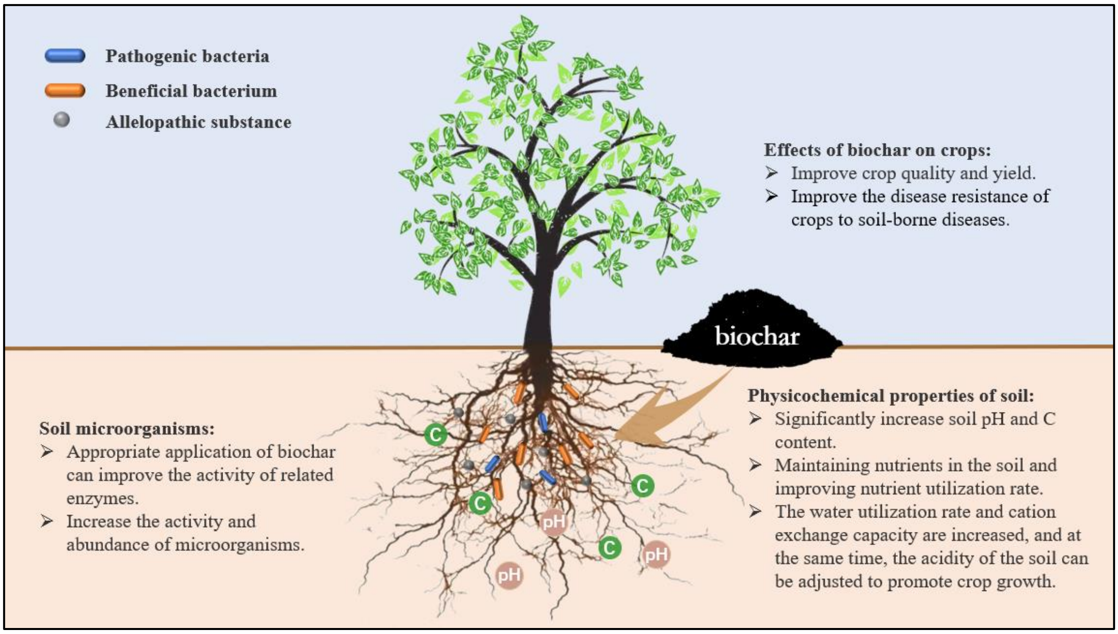

Figure 2. The mechanisms of biochar to mitigate the soil continuous cropping obstacles

4. Conclusion

Continuous cropping adversely affects soil physicochemical properties, microbial community structure, enzyme activity, etc., leading to the accumulation of autotoxic substances, the increase of soil-borne diseases, and the aggravation of soil continuous cropping obstacles. Biochar, as a new popular soil conditioner, can effectively mitigate the soil's continuous cropping obstacles. It has a good application prospect. In recent years, research on the effects of biochar combined with fertilizers and earthworms on mitigating soil continuous cropping obstacles has received increasing attention. Although biochar has been proven to be able to mitigate the soil's continuous cropping obstacles and promote the sustainable development of agriculture, the methods and techniques of its preparation are more diversified and mature nowadays. However, there are many factors affecting the effect of biochar, such as the type of biochar feedstock, pyrolysis conditions soil type, etc. The change in these factors will have a greater effect on the application of biochar. For this problem, with the current short time, small quantity, and experimental simulation but lack of practical application of the research, it still cannot be a good solution. In addition, the existing research on the adsorption of biochar on root exudates and the interaction between plants, soil, and microorganisms are relatively lacking, and the experimental results are quite different. The mechanism of action cannot be fully explained through the current research so it is impossible to better mitigate the soil continuous cropping obstacles in different types of soil by changing the preparation conditions and application amount of biochar according to the actual situation. Therefore, the above problems need to be further improved in future research.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

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