Impact of Continuous Cropping on Soil Phenolic Acid Substances and Research Progress on Continuous Cropping Obstacle Reduction Techniques

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Abstract At present, long-term continuous cropping in agricultural production has formed a relatively common development trend. With the increase of continuous cropping years, soil phenolic acids are also affected to varying degrees. This paper summarized the effects of continuous cropping on soil phenolic acids and the research progress of continuous cropping obstacle reduction techniques, aiming at providing theoretical basis and technical support for the research of continuous cropping obstacle reduction techniques and promoting the healthy and sustainable development of modern agriculture.

Key words Soil; Phenolic acid; Continuous cropping obstacle; Reduction technique; soil improvement

DOI: 10.19759/j.cnki.2164 – 4993.2024.04.014

Continuous cropping is a common phenomenon in agricultural production. However, long-term continuous cropping often leads to a series of problems, among which the accumulation of phenolic acids in soil[1] and the obstacles caused by continuous cropping[2] become important factors restricting the sustainable development of agriculture. Through in-depth research on the continuous cropping soil of soybean[4], apple[5], eggplant[6], strawberry[7], peanut[8], poplar[9] and tobacco[10], it has been found that phenolic acids accumulate in the soil and cause continuous cropping obstacles to some extent. Studies have pointed out that it is an effective way to overcome the obstacles of continuous cropping by applying soil amendments to alleviate allelopathy and restore and rebuild a healthy rhizosphere ecosystem[3]. Continuous cropping will lead to the gradual increase of phenolic acids in soil, which have a complex and far-reaching impact on soil ecosystem and crop growth and development. They may inhibit the activity of soil microorganisms, change the availability of soil nutrients, and then affect the root growth, nutrient absorption, yield and quality of crops. Facing the challenge brought by continuous cropping obstacles, researchers actively explore and study their reduction techniques. These techniques cover many aspects, such as soil improvement, crop rotation, biological control and chemical control, aiming at reducing the negative effects of phenolic acids, restoring soil health, and ensuring the normal growth and stable yield of crops. Therefore, this paper aimed to comprehensively analyze the influence mechanism of continuous cropping on soil phenolic acids and systematically sort out current research progress of continuous cropping obstacle reduction techniques. This study provides theoretical support and practical guidance for further understanding the obstacles of continuous cropping and promoting the sustainable development of agriculture.

Received: May 29, 2024 Accepted: August 3, 2024

Supported by Scientific Research Fund of Yunnan Education Department (2024Y742; 2023Y0863); National Natural Science Foundation of China (42067009); College Students' Innovative Training Plan Program of Yunnan Education Department in 2023 (S202311393044; S202311393061); Key Project of Science and Technology Program of Yunnan Province (202202AE090015).

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Types and Sources of Phenolic Acids

Phenolic acids in soil are a type of organic acids containing phenolic hydroxyl groups, which widely exist in plants and are released into soil through root exudates, residue decomposition, and other pathways. There are many kinds of these substances, including many allelochemicals. For example, cinnamic acid, vanillin, p-coumaric acid, ferulic acid, p-hydroxybenzoic acid and salicylic acid[11 – 14] have been successfully separated and identified as phenolic acids.

Root exudates are one of the main sources of phenolic acids. There are still different views on the mechanism of plant root secretion in academic circles. However, from the aspect of metabolism, it mainly involves two paths, one of which is the metabolic process of plants, and the other is the non-metabolic path. The root exudates produced by metabolic pathway are divided into two types[15], one of which is exudates produced by primary metabolism, and the other is exudates produced by secondary metabolism. Primary metabolism plays an important role in the growth and reproduction of plants. It not only provides plants with the energy and information they need, but also releases root exudates to the rhizosphere, and the release intensity is influenced by the growth ability of roots and the microecological environment of rhizosphere[16]. However, nowadays people are increasingly discovering that the secondary metabolites of plants, especially phenolic substances, play an important role in combating harsh environments and defending against external interference. More and more studies have shown that phenolic acids, secondary metabolites of roots, are a type of key allelochemicals. Phenolic acid compounds are mainly produced through shikimic acid pathway, and root exudates play a direct or indirect role in continuous cropping obstacles[17]. Generally speaking, there are four main ways for allelochemicals to enter the soil in the natural state, and the first is through volatile substances released by the plant body. Liu *et al.*[18] studied and analyzed the volatile components released by fresh cucumbers, and 36 compounds were isolated, and 29 of them were accurately identified, mainly including aromatic acids, phenolic acids and aldehydes separated from roots and plant residues. The action time of plant volatiles is short, and they generally have inhibitory effect on adjacent plant individuals. The second is through rain and fog leaching. Allelochemicals such as organic acids and phenols produced by plants are released into the environment through natural media such as rain, dew and fog by leaching. These substances may then be incorporated into the soil, or directly transferred to adjacent plants, generating a significant indirect effect on the growth of surrounding plants. Liu *et al.*[19] found that phenolic acid compounds were ubiquitous in various organs such as roots, stems and leaves of soybean, and these compounds were mainly secreted to the environment through leaves, and then entered the soil with the help of rain and fog. The third is plant secretion from the roots. Jin *et al.*[20] found that the root system of *Eupatorium adenophorum* could secrete allelochemicals, mainly phenolic acids. Zhen *et al.*[21] detected hydroxybenzoic acid and other phenolic acids from strawberry root exudates by high performance liquid chromatography. In addition, soybean roots also secrete many phenolic acids with obvious inhibitory effects, such as vanillic acid, vanillin and phthalic acid, which have obvious inhibitory effects on soybean seed germination and radicle growth[22]. The occurrence of plant continuous cropping obstacles is often closely related to the interaction of root exudates and the interaction of factors including pathogenic microorganisms in the soil and invasion by insects. The fourth is the decomposition of plant residues or litter. Guenzi *et al.*[22] found that the residues of oat, wheat, sorghum and corn all contained phenolic acids. The decay of sugarcane residues will release many harmful substances such as hydroxybenzoic acid, coumaric acid, syringic acid, ferulic acid and vanillic acid, which will also inhibit the germination and growth of ratoons. The residues of corn, oat and sorghum can generate phenolic compounds such as cinnamic acid and ferulic acid, which have inhibitory effects on the growth of crops such as soybean, sunflower and tobacco[23-25]. The study of Han *et al.*[26] proved that the organic compounds produced by soybean stubble decomposition contained some allelopathic substances, some of which not only inhibited the germination and radicle growth of soybean seeds, but also played an important role in the continuous cropping obstacles of soybean.

Accumulation of Phenolic Acids in Rhizosphere Soil Caused by Continuous Cropping

Under the condition of continuous cropping, the roots of the same crop will continuously secrete specific phenolic acids, and the types of substances secreted are relatively stable, which leads to the continuous accumulation of these substances in the soil. Ma *et al.*[27] reported that continuous cropping of cucumber would lead to the increase of phenolic acid accumulation in soil, and phenolic acids increased significantly with the increase of planting years, thus causing autotoxicity and continuous cropping obstacles. Li *et al.*[8] also found that phenolic acids in peanut root exudates accumulated in the soil under the condition of continuous cropping. The study by Yin *et al.*[28] showed that phloroglucinol, phloretin and phlorizin mainly existed in the secretion of apple seedlings, accounting for more than 80% of the total secretion. This result further confirmed that when there are autotoxic substances in the soil of apple orchards, the sources are mainly phenolic acids contained in apple root extracts. In the case of continuous cropping of flue-cured tobacco, with the increase of continuous cropping years, the content of phenolic acids in soil will increase. Bai *et al.*[10] found that long-term continuous tobacco planting would lead to an increase in soil pH and a decrease in soil organic matter content, but an increase in available potassium content; and meanwhile, the contents of hydrolyzable nitrogen and available phosphorus decreased first and then increased, while the enzyme activity increased first and then decreased. In addition, it is found that the content of phenolic acids in soil has a significant correlation with soil physical and chemical properties, enzyme activity and bacterial abundance, and the correlation with soil physical and chemical properties is highest; and there are also differences between the contents of different kinds of phenolic acids and the main environmental factors in soil. P-hydroxybenzoic acid and coumaric acid have the highest correlation with physical and chemical properties, enzyme activity and bacterial abundance of tobacco-growing soil. Taking continuous cropping of strawberry as an example, the secretion of living plants or the decomposition of residues will produce a compound belonging to phenolic acids. These compounds have strong allelopathy, and they accumulate in soil and generate adverse effects on crops in the next season. The study of Tian[29] revealed that the levels of p-hydroxybenzoic acid, cinnamic acid, ferulic acid and p-coumaric acid in soil increased obviously with the increase of continuous planting years of strawberry, especially p-hydroxybenzoic acid, which had a significant inhibitory effect on the development of roots, stems and leaves of strawberry seedlings. Such effect was particularly obvious in the fresh weights of roots and aboveground part, and hindered the improvement of root activity, and the chlorophyll content of leaves and SOD activity were also inhibited, thus weakening the disease resistance of strawberry. Crop residues after harvest are decomposed incompletely or slowly in the soil, and phenolic acids contained in the residues cannot be fully degraded and transformed by microorganisms in time, thus accumulating in the soil. Continuous cropping may also change the community structure and composition of soil microorganisms, and the species and quantity of some microorganisms that can effectively decompose phenolic acids are reduced, which inhibits the decomposition and metabolism of phenolic acids and leads to their accumulation. For example, it has been found that after continuous cropping, the content of beneficial fungi such as *Chaetomium* decreases, while the content of harmful fungi such as *Verticillium* wilt, *Fusarium* and *Colletotrichum* increased[30].

Harm of Phenolic Acid Accumulation in Soil

Inhibiting plant growth and development: Phenolic acids can inhibit the growth of plant roots, reduce the length, surface area and volume of roots, and affect the absorption of water and nutrients by roots, thus leading to slow plant growth, short plants, yellow leaves, poor flower and fruit development, and ultimately reducing crop yield and quality. For example, in peanut planting, related studies shows that continuous cropping leads to the accumulation of phenolic acids in the soil, inhibits the growth of peanut roots and plants, and reduces the yield and fruit quality[8].

Destroying the balance of soil microorganisms: Microbial communities in soil are very important for maintaining soil health and nutrient circulation. The accumulation of phenolic acids may inhibit the growth and activity of beneficial microorganisms, and promote the reproduction of harmful microorganisms, leading to the imbalance of microbial community structure and affecting the biochemical process of soil. For example, the study of Ma *et al.* [27] showed that with the increase of treatment concentration, the quantity of bacteria and actinomycetes would increase accordingly. At the concentration of 80 μg/g, the quantity of bacteria and actinomycetes was the largest, and there were significant differences from other treatments. However, when the treatment concentration further increased, the quantity of bacteria and actinomycetes decreased sharply, reaching the lowest point at the treatment concentration of 160 μg/g. It shows that low concentration of phenolic acids can promote the growth and reproduction of bacteria and actinomycetes, while high concentration of phenolic acids can inhibit their growth. Changing the physical and chemical properties of soil: Phenolic acids may affect the physical and chemical properties of soil, such as pH value, redox potential and cation exchange capacity, making the soil environment unfavorable for plant growth.

Inducing plant autotoxicity: Some phenolic acids are compounds with autotoxicity secreted by plants themselves. In the case of continuous cropping, accumulated phenolic acids will be toxic to the same plant and aggravate the obstacles of continuous cropping. The study by Wang *et al.* [31] showed that phenolic acids secreted by the roots of *Vanilla planifolia* might have autotoxic effects on themselves and affected the growth and development of *V. planifolia*. Song *et al.* [32] found that phenolic acids in *Lycium barbarum* leaves had autotoxicity. Adding dry powder of *L. barbarum* leaves to farmland soil without *L. barbarum* planting history could significantly inhibit the growth of *L. barbarum* seedlings and photosynthesis of leaves. The metabonomics of *L. barbarum* leaves at the end of the growing season was analyzed by combining UPLC-QTOF-MS and GC-TOF-MS techniques, and many organic acids were identified. Among them, salicylic acid, phthalic acid, p-hydroxybenzoic acid and coumarin still had significant inhibitory effects at low concentrations. Moreover, long-term continuous planting of *L. barbarum* led to the accumulation of coumarin, salicylic acid, benzoic acid, ferulic acid and coumaric acid in the garden soil, and the total phenolic acid content in the soil increased significantly with the increase of planting time.

Reducing the activity of soil enzymes: For example, the activities of catalase, urease, phosphatase and other enzymes are affected, and the decomposition of organic matter and the release and transformation of nutrients in soil are thus interfered. A large number of studies have shown that phenolic acids can affect the activity of enzymes. Lyu *et al.* [33] found that root exudates such as p-hydroxybenzoic acid and phenylacrylic acid significantly inhibited the activities of SOD and other enzymes in plant roots, which led to the inhibition of plant growth; and with the increase of phenolic acid concentration, the inhibitory effect on enzyme activity became more and more obvious. Huang *et al.* [34] explored the effects of phenolic acids on the activity of rhizosphere enzymes of *Panax ginseng* in the seedling stage by using a nutrient solution culture method. The results showed that benzoic acid could promote the activity of catalase (CAT) and inhibit the activity of peroxidase (POD) in rhizosphere of *P. ginseng* seedlings.

Research Progress on the Causes and Reduction Techniques of Continuous Cropping Obstacles

In 1983, Takashima[35] summarized the causes of continuous cropping obstacles and summarized five main factors: the lack of nutrients in the soil, abnormal soil response, deteriorated physical and chemical properties of soil, harmful substances released by plants, and the change of soil microorganisms. According to the research of domestic scholars, it is generally believed that the root of continuous cropping problems mainly comes from two points, one of which is the degradation of soil structure and chemical properties, such as the deterioration of soil texture, salt accumulation in cultivated layer and nutrient imbalance. The second is the disorder of soil ecosystem, which is manifested by the increase of autotoxic compound concentration and root exudates, the surge of pests and the intensification of root-knot nematodes and other diseases. At present, techniques for reducing obstacles in continuous cropping have been reported.

Crop rotation technique

Crop rotation, as an effective agricultural management measure, can not only weaken the growth and reproduction conditions of specific pathogens and reduce their number, but also help to optimize soil texture and physical and chemical characteristics and alleviate the autotoxicity caused by root exudates. Rotation is an economical and efficient method to solve the problem of continuous cropping obstacles. The study of Feng *et al.* [36] showed that the yield of peanut could be significantly improved by rotating peanut with wheat, spinach, rape and radish. Alve[37] and Zhu *et al.* [38] emphasized that selecting varieties with different genotypes for crop rotation, especially those with distant genetic relationship, or carrying out paddy-upland crop rotation, and matching crops with corresponding crops having allelopathic effects can more effectively reduce the negative impact caused by continuous cropping obstacles. The study by Wang *et al.* [39] also revealed that in the hilly red soil areas with irrigation conditions, the adoption of paddy-upland rotation has a significant effect on improving peanut yield. In addition, the occurrence probability of root rot, bacterial wilt and southern blight can be significantly reduced by rotating peanut with watermelon, sweet potato and corn, and the reduction can reach half to two-thirds of the original. The study by Nanjappa *et al.* [40] revealed the significant influence of sunshine intensity on crop yield and economic benefit in peanut and pepper rotation system. They found that with the increase of sunshine intensity, the yield and economic benefits of peanuts and peppers also increased. These results show that crop rotation can not only improve crop yield, but also reduce the occurrence of diseases, and it is a farming method worth popularizing in agricultural production.

Soil improvement techniques

Soil improvement techniques refers to improving the physical, chemical and biological properties of soil through various methods and measures to improve soil fertility, increase crop yield and improve the ecological environment. Xu *et al.* [41] deeply explored the influence of fertilization strategy on soil microbial community and soil enzyme activity in solar greenhouse through field experiments. Studies have shown that using organic fertilizers and foliar topdressing can increase the quantity of bacteria in soil; and in contrast, the use of chemical fertilizers and biogas fertilizes promote the growth of fungi. Zhu *et al.* [42] found that applying organic materials in the soil with continuous cropping obstacles could effectively alleviate this problem. Among various organic materials, pig manure had the most obvious effect, and 0.5% straw also had a certain alleviating effect, while sawdust and 1% -2% straw had poor effects. It is worth noting that no matter what kind of organic fertilizer, its effect on continuous cropping cucumber at different growth stages is similar. In the study by Zhou and Yang[43], after observing cucumber in greenhouse for 12 consecutive years, it was found that the application of bio-fertilizers such as enzyme bacterial fertilizer or bio-fermented chicken manure combined with biogas fertilizer achieved the effects of significantly promoting the growth of cucumber, reducing the occurrence of *Fusarium* wilt, increasing the yield, reducing the electrical conductivity (EC value) of soil and alleviating the phenomenon of soil salinization. Lyu *et al.* [44] pointed out that the application of organic fertilizers could alleviate the inhibitory effect of phenylacrylic acid secreted by cucumber roots on the growth of continuously-planted cucumbers, and then promote the growth and development of cucumber. Organic fertilizers can significantly improve the activities of dehydrogenase and ATPase in cucumber roots, thus enhancing its absorption efficiency of nutrients, and they can effectively boost the activity of soil microorganisms in the land where cucumber is continuously planted. In the study by Zhang and Dong[45], it was found that the application of organic fertilizers had a significant and influential change in soil microbial community. Especially when combining with inorganic fertilizers or biological fertilizers, the effect was more obvious. Compared with the control group without fertilization, the combined use of organic fertilizers and inorganic fertilizers significantly increased the quantity of bacteria in the soil, reaching 109.8%, and the number of actinomycetes surged by 320.3%. Meanwhile, the quantity of fungi decreased by 44.0%. Similarly, after the combination of organic fertilizers and biological fertilizers, the quantity of bacteria increased by an astonishing 405.0%, and the quantity of actinomycetes increased by 215.0%, while the quantity of fungi decreased by 47.2%. This result indicated that organic fertilizers showed a positive effect in alleviating the obstacles in continuous planting of cucumber caused by crop autotoxicity. To sum up, these studies highlight the potential importance and value of organic fertilizers in optimizing soil ecosystem and improving crop growth quality.

Biological control techniques

Biological control measures such as "treating bacteria with bacteria" have become a new solution. A biological protective barrier can be formed around the roots of plants by inoculating mycorrhiza, which can help to decompose harmful organic substances in soil, restore degraded or polluted soil, stabilize and increase the types and quantities of beneficial microorganisms, and enhance the stress resistance of plants, thereby improving the yield and quality of crops[46]. The studies by Enwall *et al.* [47] and Cardinale *et al.* [48] showed that a soil microbial community with reasonable structure, rich diversity and high vitality, can effectively alleviate or even eliminate continuous cropping obstacles and ensure the stability and sustainability of soil ecosystem. These research results emphasize the important role of biological control measures in modern agriculture and their potential contribution to the realization of sustainable agricultural production.

Future Research Direction and Prospects

In the future, it is suggested to focus on three core directions in the in-depth study of the influence of continuous cropping on soil phenolic acids and the exploration of continuous cropping obstacle reduction techniques. In specific, first, the internal relationship between phenolic acids and continuous cropping obstacles should be deeply understood through interdisciplinary research based on molecular mechanism exploration and development of dynamic monitoring techniques, so as to reveal its mechanism in soil microbial community change and continuous cropping obstacles. Second, we should commit to the innovation of new reduction techniques, including the application of biological techniques, the innovation of physical and chemical methods and the research and development of green and sustainable techniques, aiming to develop efficient and environmentally-friendly solutions to reduce the accumulation of phenolic acids in soil and its negative impact on crop growth. Finally, it is necessary to construct a comprehensive technical system and popularize it, and form a complete set of prevention and control strategies for continuous cropping obstacles through integration of technical schemes, technical popularization and training, and policy and market support, so as to promote the transformation of scientific research achievements into actual productivity, help the sustainable development of agriculture, and ensure the health and stability of soil ecosystem. These three directions complement each other and point to a common goal of effectively meeting the challenges brought by continuous cropping and providing solid support for efficient production of modern agriculture and environmental protection through the combination of scientific research and practical application.

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Editor: Yingzhi GUANG Proofreader: Xinxiu ZHU

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Editor: Yingzhi GUANG Proofreader: Xinxiu ZHU