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Soil Microbial Community Dynamics in Continuous Strawberry Cultivation Systems

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Abstract Strawberry (*Fragaria* × *ananassa* Duch.) is one of the world's most important economic berry crops, playing a vital role in protected agriculture and efficient horticultural production systems. With the continuous expansion of strawberry cultivation, continuous cropping has become widely adopted in production practices. However, long-term continuous cropping often leads to soil ecological degradation and cropping obstacles, with changes in soil microbial community structure considered a key driving factor. In recent years, with the development of high-throughput sequencing technology and microbial ecology research, the dynamics and ecological functions of microbial communities in strawberry continuous cropping systems have gradually become an important direction in agricultural ecology research. This paper systematically reviews the basic characteristics of soil ecological environment changes under continuous strawberry cultivation conditions, focusing on the succession patterns of bacterial and fungal community structure and diversity, and elucidating the regulatory effects of root exudates, soil physicochemical factors, and agricultural management practices on microbial communities. Furthermore, it explores the ecological relationship between microbial community changes and strawberry cropping obstacles, and summarizes management strategies for regulating soil microbial community structure through measures such as organic fertilizers, bio-inoculants, and crop rotation. Through a case study of a typical continuously cropped strawberry field, the impact of increased continuous cropping years on soil health and microbial community stability is revealed. This article aims to provide theoretical reference and practical basis for soil ecological management and sustainable production of strawberry continuous cropping.

Keywords Strawberry (*Fragaria* × *ananassa* Duch.); Continuous cultivation; Soil microbial community; Continuous cropping obstacles; Rhizosphere ecology

1 Introduction

Strawberries, belonging to the Rosaceae family, are perennial herbaceous plants and one of the most important berry-based economic crops widely cultivated worldwide (Kumar et al., 2025; Quddus et al., 2025). In recent years, with the development of facility agriculture and the continuous growth of market demand, the strawberry planting area has been expanding, especially in greenhouse and high-efficiency agricultural production areas, where strawberries have become an important industry for increasing farmers' income (Samtani et al., 2019). Due to the high economic value, relatively short production cycle, and stable market demand of strawberries, many planting areas have gradually formed a specialized production model centered on strawberries (Xie et al., 2021; Yang and Kim et al., 2023; Zacharaki et al., 2024).

In actual production, to improve land use efficiency and reduce crop rotation costs, strawberries are often cultivated on the same plot of land for many consecutive years (Bai et al., 2025). While continuous cultivation can maintain stable yields and reduce production inputs in the short term, long-term continuous cropping leads to a series of changes in the soil ecological environment, such as nutrient imbalance, soil structure deterioration, and pathogen accumulation (Yang et al., 2023). These changes not only affect crop growth but may also lead to decreased yields and reduced quality, thus limiting the sustainable development of the strawberry industry (Wu et al., 2025).

Continuous cropping obstacles refer to a series of adverse phenomena that occur after the same crop is planted on the same land for a long period of time, including poor crop growth, increased pests and diseases, and decreased yield and quality. As a shallow-rooted crop, strawberries are highly sensitive to changes in the soil environment, making them more susceptible to continuous cropping obstacles under continuous cultivation conditions (Chen et al., 2022). Soil health is a key indicator of the sustainability of agro-ecosystems. Healthy soil typically has a good structure, sufficient organic matter content, and a stable microbial community structure (Zha et al., 2024). However, during continuous strawberry cropping, due to long-term monotonous fertilization, fixed farming methods, and the accumulation of crop residues, the physical and chemical properties of the soil often change. For example, problems such as soil acidification, accelerated organic matter decomposition, and nutrient imbalance gradually emerge. At the same time, continuous cropping also leads to the gradual accumulation of certain soil-borne pathogens in the soil, thereby increasing the risk of disease occurrence. Common soil-borne diseases of strawberries include Fusarium wilt, root rot, and Verticillium wilt (Lazcano et al., 2021). These diseases are often closely related to changes in the soil microbial community structure; therefore, in-depth research on microbial community changes in continuous cropping systems is of great significance for revealing the mechanisms of continuous cropping obstacles.

Soil microorganisms are an important component of soil ecosystems, encompassing diverse microbial groups such as bacteria, fungi, actinomycetes, and archaea. These microorganisms exert significant influence on agro-ecosystems through their participation in processes such as organic matter decomposition, nutrient mineralization, and rhizosphere interactions. In crop production systems, microbial communities not only affect soil nutrient cycling but also promote plant growth in various ways. For example, some rhizosphere bacteria can promote plant growth through nitrogen fixation or the production of plant hormones, while certain antagonistic microorganisms can inhibit the growth of soil-borne pathogens, thereby reducing disease incidence. Furthermore, soil microbial community structure is considered an important indicator for evaluating soil ecological stability. Significant changes in microbial community structure often signify alterations in soil ecological functions. Therefore, studying microbial community dynamics in strawberry continuous cultivation systems is of great value for understanding the succession process of agro-ecosystems.

2 Soil Ecological Characteristics of Continuous Strawberry Cultivation Systems

2.1 Changes in soil physicochemical properties under continuous cultivation conditions

Under continuous cultivation conditions, soil physicochemical properties often undergo significant changes. First, long-term application of chemical fertilizers may gradually exacerbate soil acidification, thereby affecting the availability of nutrients in the soil (Ding et al., 2024). Second, excessive fertilization may also lead to soil salt accumulation, adversely affecting strawberry root growth (Neina et al., 2019; Zha et al., 2024). Furthermore, continuous cultivation alters soil organic matter content. Strawberry production typically requires the application of large amounts of organic fertilizer, but in some cases, the rate of organic matter decomposition may outpace its replenishment, resulting in a decrease in soil organic matter content. Reduced soil organic matter not only affects soil structure but also lowers the quality of the living environment for soil microorganisms. Therefore, in strawberry continuous cropping systems, changes in soil physicochemical properties are often closely related to changes in microbial community structure.

2.2 Strawberry rhizosphere environment and microbial habitat conditions

The rhizosphere refers to the soil region surrounding a plant's roots, influenced by root activity, and is one of the most active areas for microbial activity (Lazcano et al., 2021). During growth, strawberry roots release various organic substances, such as sugars, organic acids, and amino acids, which provide carbon and energy sources for microorganisms (Su et al., 2022). The unique characteristics of the rhizosphere environment often lead to the formation of a distinctive microbial community structure. Some microorganisms adapt to the rhizosphere and form mutually beneficial relationships with the plant, while others may become potential pathogens (Kwak et al., 2025). Therefore, the structure of the strawberry rhizosphere microbial community can undergo significant changes during continuous cultivation, and these changes have a crucial impact on crop health.

2.3 The impact of continuous cropping on soil ecosystem stability

Soil ecosystem stability is a crucial foundation for sustainable agricultural production. Under long-term continuous cropping conditions, soil ecosystems often face multiple pressures, including nutrient imbalances, decreased microbial diversity, and pathogen accumulation. When ecosystem stability decreases, the soil's resistance to changes in the external environment weakens. For example, under conditions of high temperature or drought, soil microbial communities may experience drastic fluctuations, further impacting crop growth (Pinto-Poblete et al., 2022; He et al., 2023). Therefore, maintaining soil ecosystem stability is one of the important goals of strawberry continuous cropping management.

3 Changes in Soil Microbial Community Structure and Diversity

3.1 Bacterial community structure and its succession characteristics

In continuous strawberry cultivation systems, bacterial communities are typically the most numerous and ecologically active group of microorganisms in the soil microbial community. With increasing years of continuous cropping, the structure of the soil bacterial community often exhibits significant succession (Chen et al., 2022). In the initial stages of continuous cropping, the soil bacterial groups are relatively abundant and diverse, with various bacteria forming relatively stable complementary relationships in ecological functions (Huang et al., 2018). However, as the continuous cultivation period extends, soil environmental conditions gradually change, such as a single source of organic matter, altered nutrient ratios, and the accumulation of root exudates. These factors exert selective pressure on the bacterial community structure. Some bacterial groups adapted to specific environmental conditions gradually become dominant, while bacterial groups more sensitive to environmental changes may decrease or even disappear, leading to a gradual simplification of the community structure. Simultaneously, certain bacteria involved in organic matter decomposition and nutrient cycling may exhibit strong adaptability in continuous cropping environments, playing a crucial role in maintaining basic soil ecological functions (Adhikari et al., 2025). Therefore, bacterial community succession not only reflects the adaptation process of microorganisms to environmental changes but also, to some extent, reveals the trend of changes in soil ecosystem structure.

3.2 Changes in fungal community composition and pathogenic microorganisms

Compared to bacteria, fungi also play a crucial role in soil ecosystems. Fungi not only participate in the decomposition of organic matter and soil structure formation, but also have complex ecological interactions with plant roots (Lazcano et al., 2021). Under continuous strawberry cultivation conditions, the composition of the fungal community often changes significantly with the increase in the number of consecutive cropping years. In the early stages of cultivation, the soil usually contains abundant saprophytic fungi, which can effectively decompose plant residues and participate in soil organic matter cycling. However, with prolonged continuous cropping, certain fungal groups adapted to specific rhizosphere environments gradually accumulate, some of which may be potential pathogens . Because strawberry roots continuously release specific types of organic matter, these substances provide suitable growth conditions for certain fungi, leading to a gradual increase in their numbers. When the proportion of pathogenic fungi increases, the soil microecological balance may be disrupted, thereby increasing the risk of root diseases. Therefore, changes in fungal community structure are significant in the formation of strawberry continuous cropping obstacles, and studying their changing patterns helps to better understand the mechanisms of soil microecological succession.

3.3 Microbial diversity index and community stability analysis

Microbial diversity is a crucial indicator for assessing the health of soil ecosystems. It is typically reflected in indicators such as species richness, community evenness, and diversity indices. In strawberry continuous cropping systems, soil microbial diversity often changes to varying degrees with increasing cropping duration. In the early stages of cultivation, due to relatively stable soil conditions, the microbial community structure is complex, and stable ecological relationships are formed among various microorganisms. However, as the continuous cropping period lengthens, the soil environment gradually changes, and some environmentally sensitive microorganisms may decrease, leading to a decline in overall diversity (Han et al., 2025). When the microbial community structure becomes relatively homogeneous, the stability of the soil ecosystem may also decrease. Highly diverse microbial communities generally possess strong ecological regulation capabilities, maintaining nutrient cycling and ecological balance. Therefore, in strawberry continuous cropping systems, improving microbial diversity levels helps enhance the stability of the soil ecosystem, thereby providing a favorable ecological environment for healthy crop growth (Adhikari et al., 2025).

4 Main factors affecting soil microbial community in strawberry continuous cropping

4.1 The regulatory role of root exudates on the microbial community

Plant root exudates are a crucial ecological factor influencing soil microbial community structure. During strawberry growth, the plant releases various organic compounds through its roots, including sugars, organic acids, amino acids, and phenolic compounds (Wen et al., 2022). These compounds not only provide carbon and energy sources for microorganisms but also selectively influence different microbial groups (Afzal et al., 2024). Under continuous cultivation conditions, the long-term accumulation of root exudates gradually alters the soil microbial environment. Microorganisms capable of utilizing these organic substances tend to increase, while those less adaptable may decrease. Furthermore, some root exudates possess antibacterial or regulatory effects, affecting the growth and reproduction of specific microorganisms (Zhang et al., 2023). Over time, this selective effect may lead to gradual changes in the microbial community structure. Therefore, root exudates play a key role in the regulation of soil microecology during strawberry continuous cropping and are a significant driving force influencing microbial community succession.

4.2 Influence of soil physicochemical factors (pH, organic matter, nutrients, etc.)

Soil physicochemical properties are crucial environmental conditions that determine the structure of microbial communities, with pH, organic matter content, and nutrient status being particularly critical (Gao et al., 2024). Different microbial groups have varying degrees of adaptability to soil environmental conditions, and changes in soil physicochemical properties lead to adjustments in the microbial community structure (Bai et al., 2023). For example, changes in soil pH directly affect microbial metabolic activities; some microorganisms thrive in neutral environments, while others are more adapted to acidic environments. Under continuous strawberry cultivation conditions, long-term fertilization often exacerbates soil acidification, thereby altering the microbial community structure (Gao et al., 2024). Furthermore, soil organic matter is an important energy source for microorganisms; increased organic matter content typically promotes microbial reproduction and enhances community diversity. Nutrient supply also affects microbial activity; different nutrient ratios can alter the competitive relationships among microorganisms. Therefore, the rational regulation of soil physicochemical properties is of great significance for maintaining the stability of microbial communities (Adhikari et al., 2025).

4.3 The role of agricultural management measures (fertilization, irrigation, pesticides)

Agricultural management practices are significant anthropogenic factors influencing soil microbial communities (Li et al., 2021). In strawberry production, fertilization methods, irrigation management, and pesticide use all impact soil microbial ecology. Different fertilization structures alter soil nutrient sources, thus affecting microbial community composition (Zha et al., 2024; Maková et al., 2025). For example, long-term use of chemical fertilizers alone may lead to a decline in microbial diversity, while the application of organic fertilizers provides abundant organic carbon sources for microorganisms, promoting the reproduction of beneficial microorganisms . Irrigation conditions also significantly affect microbial activity. Suitable water conditions promote microbial metabolism, while excessive irrigation may reduce soil aeration, inhibiting the growth of certain aerobic microorganisms. Furthermore, pesticides, while controlling pests and diseases, may also affect some microorganisms. Therefore, rationally optimizing agricultural management practices is crucial for maintaining soil microecological balance in strawberry production.

5 The Relationship between Microbial Community Change and Strawberry Continuous Cropping Obstacles

5.1 Accumulation mechanism of soil-borne pathogens

In continuous strawberry cultivation, soil-borne pathogens tend to accumulate in the soil with increasing years of continuous cropping (Huang et al., 2018). Because strawberries are continuously grown in the same plot, pathogens have a stable source of hosts for a long period, allowing them to survive and reproduce (Lazcano et al., 2021). Simultaneously, strawberry root exudates and residual root tissue provide a suitable nutrient environment for some pathogens, enabling them to persist and spread in the soil. As the planting cycle lengthens, the number of these pathogens in the soil gradually increases, potentially forming a relatively stable community structure. When the number of pathogens reaches a certain level, the strawberry plants' disease resistance becomes insufficient to resist infection, leading to various soil-borne diseases such as root rot and wilt. Furthermore, the soil ecological environment gradually changes under continuous cropping conditions, reducing the number of certain beneficial microorganisms, further weakening their inhibitory effect on pathogens, thus promoting their accumulation and spread. Therefore, the continuous accumulation of soil-borne pathogens is considered one of the important reasons for the problems associated with continuous cropping in strawberries.

5.2 Reduction of beneficial microbial communities and ecological imbalance

In a healthy soil ecosystem, a relatively stable ecological balance is usually maintained between beneficial and pathogenic microorganisms (Lazcano et al., 2021). Beneficial microorganisms exert a natural inhibitory effect on pathogens by competing for nutrients, producing antimicrobial substances, or inducing plant resistance. However, under continuous strawberry cultivation conditions, this balance may gradually be disrupted. As the number of consecutive cropping years increases, soil environmental conditions change, and the number of some beneficial microorganisms that are more sensitive to environmental changes may gradually decrease. At the same time, some microorganisms with strong adaptability may become dominant groups, but their ecological functions may not necessarily be conducive to maintaining soil healt. When the size of the beneficial microbial community shrinks, the original ecological regulation mechanisms in the soil are weakened, making it easier for pathogenic microorganisms to gain a dominant position. This imbalance within the ecosystem not only affects the structure of the microbial community but also further affects soil nutrient cycling and the plant growth environment. Therefore, the reduction of beneficial microorganisms is considered an important factor that cannot be ignored in the formation of continuous cropping obstacles.

5.3 Effects of changes in microbial community structure on strawberry growth and yield

Changes in soil microbial community structure have multifaceted impacts on strawberry plant growth (Yang et al., 2023). When beneficial microorganisms decrease while pathogenic microorganisms increase, strawberry roots become more susceptible to infection, affecting their ability to absorb water and nutrients (Figure 1) (Zhang et al., 2023). Impaired root function weakens the overall growth vigor of the plant, manifesting as slow leaf growth and poor fruit development. Furthermore, changes in the soil microbial community can also affect nutrient cycling processes (Zha et al., 2024). For example, a decrease in the number of certain microorganisms involved in nitrogen cycling and organic matter decomposition can reduce soil nutrient supply efficiency, further impacting plant growth. Under long-term continuous cropping conditions, these adverse factors accumulate, ultimately leading to decreased strawberry yield and reduced fruit quality. Therefore, maintaining a stable soil microbial community structure is crucial for ensuring sustained high strawberry yields.

6 Regulating Soil Microbial Communities in Continuous Strawberry Cropping

6.1 The effects of applying organic fertilizer and bio-organic fertilizer

Organic fertilizers play a vital role in improving the soil's ecological environment (Bai et al., 2025). Compared to single chemical fertilizers, organic fertilizers not only replenish soil nutrients but also increase soil organic matter content, thereby improving soil structure and water and fertilizer retention capacity (Adhikari et al., 2025). Once in the soil, organic fertilizers provide abundant carbon sources and nutrients for microorganisms, promoting their growth and reproduction, thus enhancing soil microbial activity. In continuous strawberry cultivation systems, the rational application of organic fertilizers can effectively improve the soil's micro-ecological environment, increase the number of beneficial microorganisms, and, to some extent, inhibit the growth of pathogens (Song et al., 2023). Bio-organic fertilizers are a new type of fertilizer made by adding specific beneficial microorganisms to organic fertilizers (Tao et al., 2020). These microorganisms can colonize the soil and perform various ecological functions, such as promoting nutrient transformation and inhibiting pathogens. Therefore, the rational application of organic fertilizers and bio-organic fertilizers in continuously cropped strawberry fields is crucial for restoring soil microbial diversity and improving soil health.

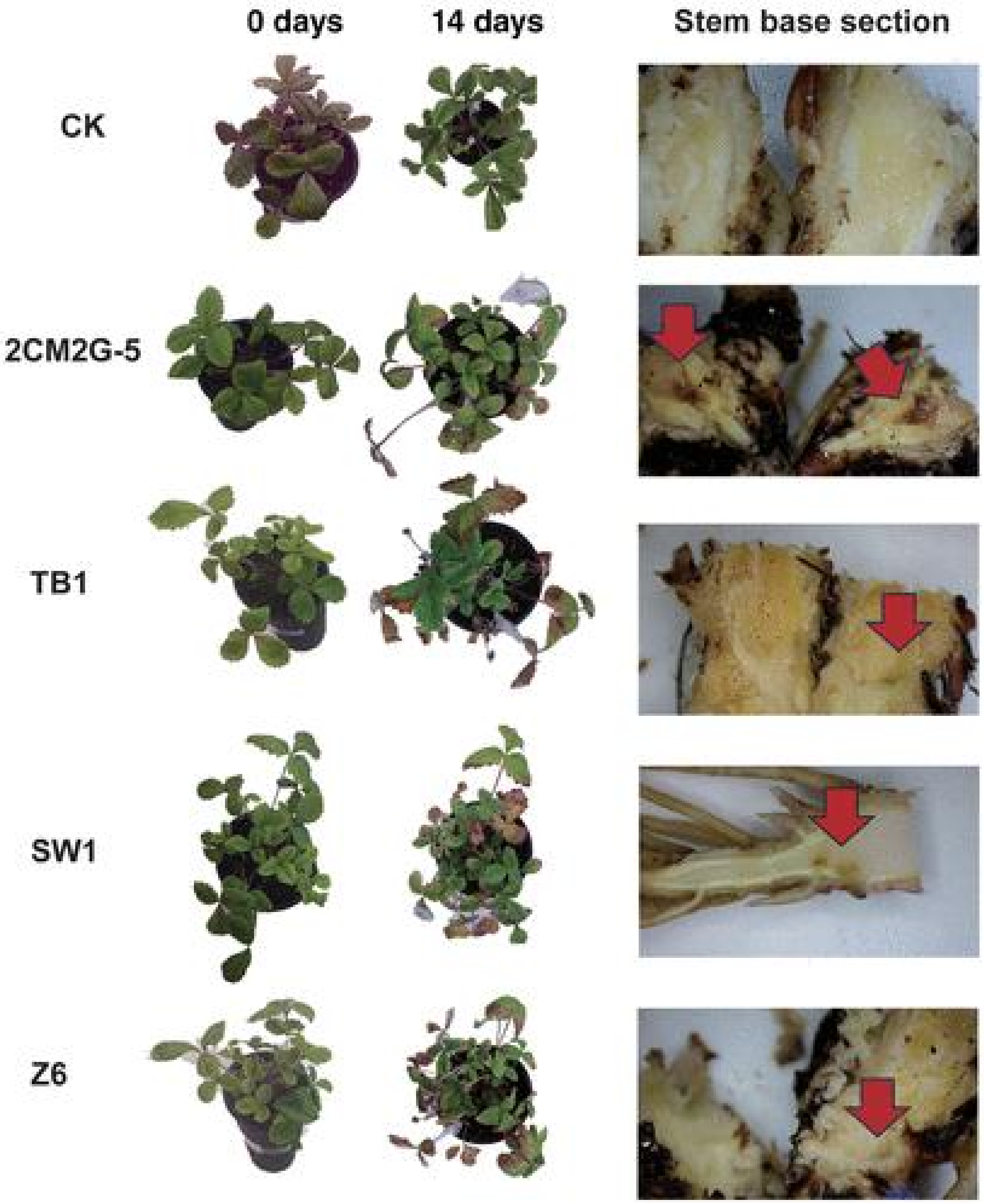

Figure 1 Comparison of the pathogenicity of strains Z6, 2CM2G-5, TB1, and SW1 with that of an uninoculated control plant (CK) (Adopted from Zhang et al., 2025)

6.2 Regulatory role of microbial inoculants and biocontrol bacteria

In recent years, the application of microbial inoculants in agricultural production has been increasing . Microbial inoculants are typically composed of microorganisms with specific functions, such as bacteria that promote plant growth or biocontrol bacteria with antagonistic effects (Maková et al., 2025). These microorganisms can influence the soil microbial community structure through various mechanisms. For example, some biocontrol bacteria can produce antimicrobial substances, inhibiting the growth of pathogens and thus reducing disease occurrence (Jiang et al., 2025). Simultaneously, some growth-promoting bacteria can enhance plant growth vigor by secreting plant hormones or promoting nutrient absorption. In strawberry continuous cropping systems, the rational use of microbial inoculants can regulate the soil microbial community structure, increase the proportion of beneficial microorganisms, and inhibit the spread of pathogenic microorganisms. Furthermore, microbial inoculants can also promote the restoration and stability of the soil ecosystem and improve soil ecological functions (Figure 2) (Dai et al., 2025). Therefore, the application of microbial inoculants in strawberry continuous cropping soil management has promising development prospects (Jiang et al., 2025).

Figure 2 Strategies for regulating soil microbial communities in continuous strawberry cropping systems

6.3 Crop rotation, intercropping and soil improvement measures

Crop rotation is a crucial agricultural measure for mitigating continuous cropping obstacles (Deng et al., 2022). By planting different crops in different growing seasons, the life cycles of certain pathogens can be disrupted, thereby reducing their accumulation in the soil. For example, rotating strawberries with other non-host crops can effectively reduce the number of pathogens in the soil. Furthermore, intercropping can increase soil plant diversity, providing diverse habitats for different types of microorganisms and promoting a stable microbial community structure (Laugale et al., 2023). Besides adjusting planting systems, soil improvement measures also play a vital role. For instance, adding straw, organic matter, or soil conditioners can improve soil structure and nutrient status, providing a more suitable environment for microbial growth. The comprehensive use of crop rotation, intercropping, and soil improvement measures helps restore the balance of the soil ecosystem, thereby mitigating the adverse effects of continuous strawberry cropping.

7 Case Study: Soil Microbial Community Succession Analysis in a Typical Strawberry Continuous Crop Field

7.1 Study area and experimental design

In typical strawberry-growing areas, the number of consecutive cropping years often varies significantly across different plots, providing excellent conditions for studying changes in soil microbial communities (Huang et al., 2018). In case studies, representative strawberry-growing areas can be selected as research subjects, and plots can be divided into different types based on the number of consecutive cropping years, such as newly cultivated plots, plots with three years of consecutive cropping, and plots with more than five years of consecutive cropping (Yang et al., 2023). Soil samples are collected from each plot, and their physicochemical properties and microbial communities are analyzed. Simultaneously, by recording the growth status and yield indicators of strawberry plants, the relationship between changes in soil microbial communities and crop growth can be further analyzed. This comparative research method can intuitively reveal the impact of consecutive cropping years on the soil ecological environment and provide a scientific basis for subsequent soil management measures.

7.2 Changes in microbial communities revealed by high-throughput sequencing

With the development of molecular biology techniques, high-throughput sequencing technology has been widely used in soil microbiology research. Sequencing analysis of soil samples from different years of continuous cropping can provide detailed information on the composition of bacterial and fungal communities in the soil (Su et al., 2022). The results typically show significant differences in the structure of soil microbial communities at different stages of continuous cropping (Figure 3) (Huang et al., 2018). In the early stages of continuous cropping, soil microbial diversity is high, and various microorganisms form a relatively complex ecological network. However, as the duration of continuous cropping increases, some microbial groups gradually become dominant, while some rare groups gradually decrease. Furthermore, high-throughput sequencing can reveal the changing trends of potential pathogens, providing important evidence for analyzing the formation mechanisms of continuous cropping obstacles. This technique allows for a more comprehensive understanding of the dynamic changes in the microbial community within strawberry continuous cropping systems.

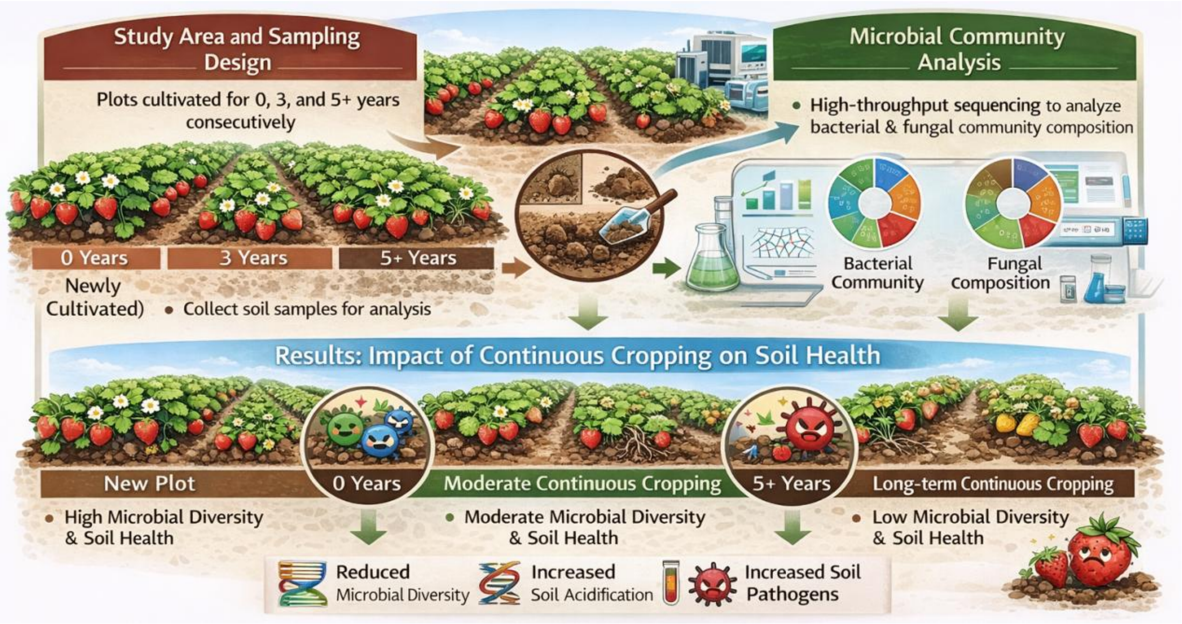

Figure 3 Case study analysis of soil microbial community succession in a typical strawberry continuous crop field

7.3 Results of continuous cropping years and soil health assessment

Comprehensive analysis of soil samples from different years of continuous cropping reveals a clear relationship between soil health and the duration of continuous cropping (Yang et al., 2023). Generally, plots with shorter periods of continuous cropping exhibit better soil structure, higher microbial diversity, and relatively better strawberry plant growth (Liu et al., 2021). However, as the duration of continuous cropping increases, soil physicochemical properties gradually change, such as a decrease in organic matter content and an increase in soil acidification. Simultaneously, the microbial community structure also shows significant adjustments. In some long-term continuous cropping plots, the proportion of pathogenic microorganisms has increased significantly, while the number of beneficial microorganisms has decreased relatively. These changes often correspond to poor strawberry plant growth and reduced yield. Therefore, a comprehensive evaluation of soil physicochemical properties and microbial community structure can accurately reflect soil health and provide a basis for developing reasonable soil management measures.

8 Conclusions and Future Research Prospects

Existing research reveals that the soil microbial community structure in strawberry continuous cropping systems gradually changes with increasing years of continuous cropping. Generally, soil microbial diversity is high and the community structure is relatively stable in the early stages of continuous cropping. However, as the continuous cropping period extends, some microbial groups gradually become dominant, leading to a more homogenous community structure. Simultaneously, some soil-borne pathogens accumulate under suitable conditions, while the number of some beneficial microorganisms may decrease. This change in community structure not only reflects changes in the soil ecological environment but also affects the growth of strawberry plants to some extent. Therefore, studying the dynamics of the microbial community in strawberry continuous cropping systems is of great significance for understanding the mechanisms of continuous cropping obstacles.

In recent years, improving the soil ecological environment using microbial regulation technology has gradually become an important direction in agricultural research. By rationally applying organic fertilizers, bio-organic fertilizers, and microbial inoculants, the soil microbial community structure can be adjusted to a certain extent, increasing the number of beneficial microorganisms and thus inhibiting the growth of pathogens. Furthermore, combining crop rotation systems and soil improvement measures can further improve soil ecological conditions and promote the recovery and stability of the microbial community. Practice has shown that when the soil micro-ecological environment is improved, the growth status and yield of strawberry plants also increase accordingly. Therefore, microbial regulation technology has great application potential in alleviating the obstacles of continuous cropping in strawberries.

Future research on soil microorganisms in strawberry continuous cropping systems holds vast potential. On one hand, multi-omics technologies can be combined to conduct deeper analyses of microbial community structure and function, leading to a more comprehensive understanding of the role of microorganisms in soil ecosystems. On the other hand, long-term field experiments can be conducted to study the impact of different agricultural management practices on microbial communities, exploring more scientific soil management models. Furthermore, with the deepening of microbial resource research, screening for functional microorganisms capable of promoting plant growth and inhibiting pathogens will become an important direction for future research. Through the comprehensive application of multidisciplinary technologies, it is hoped that the patterns of microbial community change in strawberry continuous cropping systems can be further revealed, providing new theoretical foundations and technical support for sustainable agricultural development.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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