

Optimizing soil fertility in southern China: a review of sugarcane intercropping strategies

Wenlong ZHANG*¹, Jinhua SHAO*^{1,2}, Kai HUANG (✉)², Limin CHEN³, Guanghui NIU³, Benhui WEI⁴, Guoqin HUANG (✉)¹

1 Key Laboratory of Crop Physiology, Ecology and Genetics Breeding, School of Agricultural Sciences, Jiangxi Agricultural University, Nanchang 330045, China.

2 Guangxi Hydraulic Research Institute, Guangxi Key Laboratory of Water Engineering Materials and Structures, Nanning 530023, China.

3 Irrigation Experiment Station of Qinzhou City, Qinzhou 535000, China.

4 Cash Crops Research Institute, Guangxi Academy of Agricultural Sciences, Nanning 530007, China.

*These authors contribute equally to the work

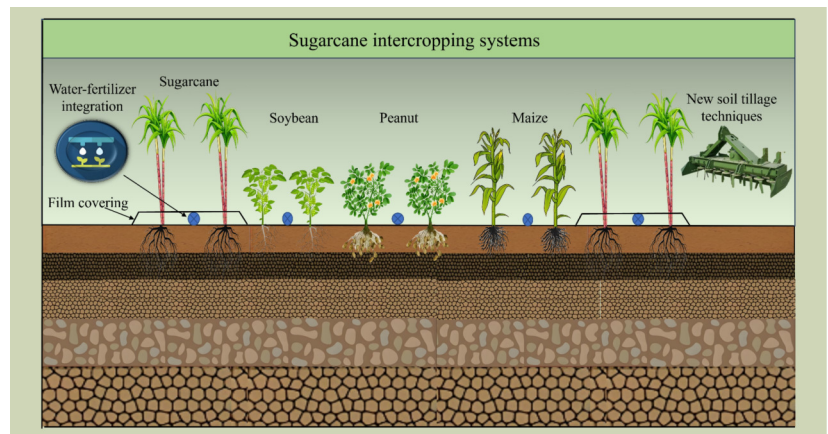
KEYWORDS

Arable land quality, dry sloping fields, intercropping, sugarcane

HIGHLIGHTS

- Sugarcane intercropping enhances soil quality: intercropping systems significantly improve soil physical properties, such as structure, porosity, and aggregate stability, contributing to enhanced soil health and water retention.
- Increased soil fertility through crop interactions: sugarcane intercropping boosts key soil nutrients, including nitrogen, phosphorus, potassium, and organic matter, through synergistic interactions with legumes and green manure crops.
- Diversified microbial communities for soil health: the practice of sugarcane intercropping promotes microbial diversity in the rhizosphere, enhancing soil microbial biomass, which plays a crucial role in improving soil fertility and agricultural productivity.
- Sustainable agricultural practices to combat soil degradation: by reducing reliance on monoculture and chemical fertilizers, sugarcane intercropping mitigates soil degradation, enhances crop yield stability, and reduces pest and disease incidence.
- Future focus on technological integration for sustainability: future research should focus on optimizing intercropping patterns, integrating water-fertilizer technologies, and evaluating long-term impacts of intercropping

GRAPHICAL ABSTRACT



ABSTRACT

Intercropping has emerged as a pivotal strategy in modern ecological agriculture, significantly contributing to biodiversity enhancement, ecological system services and soil quality improvement. In light of global food security challenges and the scarcity of arable land, intercropping is anticipated to become increasingly important for enhancing farmland quality and ensuring food security in China. Current research primarily highlights the benefits of intercropping in improving farmland quality and crop productivity, with some attention also given to its role in promoting biodiversity and ecological system services. However, the mechanisms by which intercropping specifically enhances soil physical, chemical and biological properties to sustain long-term soil health and improve farmland quality require further investigation. This review examines the concept of sugarcane intercropping and its role in promoting soil health and enhancing ecological system services. It systematically synthesizes recent research findings on the effects of sugarcane

on soil health under varying climatic conditions.

intercropping on soil physical, chemical and biological properties in southern China. Additionally, this review outlines future research directions and priorities for developing intercropping systems that prioritize farmland quality improvement, aiming to provide insights into the broader value that intercropping in China's strategies for farmland quality enhancement.

Received September 4, 2024;

Accepted January 22, 2025.

Correspondences: gxhuangkai@126.com,
hgqmail441@sohu.com

© The Author(s) 2025. Published by Higher Education Press. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0>)

1 Introduction

Arable land is essential for food production, and its sustainable management is vital for long-term food security^[1,2]. Economic growth in China and rising per capita income have increased demand for food and agricultural products, putting immense pressure on the agricultural system to boost yields and meet market needs^[3,4]. This demand has led to substantial investments in land, water and energy for crop and livestock production. However, these resources are finite and cannot be exploited indefinitely without compromising sustainability. The expansion of farmland and large-scale irrigation threaten to overexploit land and water resources, further damaging the environment and ecosystems^[4,5]. The rapid economic and social development has led to the widespread adoption of unsustainable farming practices, such as the excessive use of fertilizers and pesticides, resulting in the decline of soil quality in agricultural land^[6,7]. In dryland agricultural areas of southern China, where farmland is mainly in mountainous regions, severe soil erosion, nutrient imbalances and reduced soil biota threaten sustainable land use and national food security^[8].

Sugar is a strategic commodity for the national economy and social development in China, making a key contribution to food supply, food processing, agricultural development and national security^[9,10]. As a major producer and consumer of sugar, sugarcane production is a key part of the national agricultural economy, ranking fourth in both production and value, after grains, oilseeds and cotton^[11,12]. Sugar production in China mainly relies on sugarcane and sugar beet, with sugarcane being the main crop. This tall, perennial C₄ grass is grown mainly in tropical and subtropical regions and is one of the principal economic crops in dry, sloped areas in southern China. Globally, sugarcane is a key sugar crop with significant potential as a bioenergy source^[13,14]. In southern China, favorable climatic conditions, such as abundant sunlight and suitable temperatures, create an ideal environment for

sugarcane growth^[12,14]. However, the development of the sugarcane industry in China faces challenges including low large-scale production, limited mechanization, weak infrastructure, lack of genetic diversity, suboptimal planting and frequent natural disasters. Rising input and labor costs have further diminished farmer enthusiasm for sugarcane production^[15,16].

Intercropping, a fundamental practice in modern ecological agriculture, offers a promising solution to these challenges. Intercropping, practiced globally, is a vital technique for achieving sustainable agricultural development. China has a long history of intercropping, with evidence dating back to the Han Dynasty^[16]. Over time, this practice has evolved to include the spatial arrangement of crops at varying heights and the temporal coordination of early, mid-, and late-maturing cultivars, reflecting the early advancements in intercropping in China. As food demand grows and arable land becomes scarcer, intercropping will make a crucial contribution to enhancing biodiversity, ecosystem services and land productivity^[17]. This approach has become a focal point of interdisciplinary research in fields such as ecology, soil science, agronomy and microbiology^[2]. While current research primarily focuses on role of intercropping in enhancing biodiversity and ecosystem services, its potential to improve soil quality, especially in sugarcane production, has received less attention. Studies show that intercropping systems, such as those with leguminous or cover crops, optimize resource use, improve soil fertility and reduce pest pressures, leading to significant increases in sugarcane productivity. For example, Singh et al.^[18] found that intercropping sugarcane with crops like mustard or potato enhances soil quality, functional diversity, and overall crop productivity in subtropical regions. Similarly, Shukla et al.^[19] highlighted that in irrigated agricultural systems, intercropping legumes, oilseeds, vegetables, grains and medicinal crops with sugarcane can increase the yield of certain crops, improve soil fertility and support sugarcane growth. Additionally, intercropping

enhances farm profitability, mitigates monsoon risks and promotes agricultural sustainability. These findings highlight the potential of intercropping to enhance both sugarcane productivity and farmland sustainability.

This paper provides an overview of sugarcane intercropping, analyzing its crucial contribution to improving soil health and enhancing ecosystem services. It systematically reviews recent advancements in research on how sugarcane intercropping influences soil physical, chemical and biological properties. Additionally, this paper outlines key research priorities and challenges for the development of intercropping practices focused on enhancing soil quality, particularly in the context of agricultural strategies for improving soil conditions in the arid slopes of southern China. This analysis aims to offer practical insights for promoting the broader application of sugarcane intercropping in sustainable land management.

2 Theoretical basis and significance of sugarcane intercropping

2.1 Nature of intercropping

The ecological and environmental challenges of long-term intensive monoculture have made the need for innovative concepts and approaches to establish sustainable agricultural ecosystems increasingly urgent in modern agriculture. Diversified agricultural systems that integrate species with distinct functional roles are essential for enhancing resilience to growing environmental constraints, such as climate change and water scarcity^[20,21]. Recently, the rise of green and sustainable agriculture has brought intercropping to the forefront due to its benefits in enhancing ecological services, sustainable productivity and soil quality^[22].

Intercropping involves growing two or more crop species simultaneously or in staggered time frames on the same farmland. This method optimizes the spatial and temporal use of light, water, nutrients and other resources, thereby improving land-use efficiency and crop yields. The synergistic interactions among crops in intercropping systems can reduce pests and pathogen populations, protect and enhance soil quality, and increase ecosystem stability and sustainability^[23,24]. Intercropping systems function across temporal and spatial dimensions, embodying complex ecological principles and concepts including biodiversity, plant interactions and soil multifunctionality. This approach increases the cropping index, stabilizes ecosystem productivity, elevates crop yields per unit area and enhances economic

returns to farmers. It also addresses issues such as increased production inputs, soil degradation, inefficient use of soil nutrients and natural resources and environmental pollution^[25]. Compared to monoculture, intercropping is characterized by rich species diversity and spatiotemporal distribution, including crop combination intensity and the proportion of cover crops. These features are crucial for optimizing crop production, maintaining soil biodiversity, improving nutrient use efficiency and sustaining soil health^[26].

2.2 Sugarcane intercropping in Southern China

In recent years, sugarcane intercropping has become widely recognized as an effective production method in southern China^[27,28]. Initially, sugarcane was mainly intercropped with legumes, including soybeans^[29–31], mung beans^[32], mucuna^[33,34] and peanuts^[35,36]. Over time, this practice has expanded to include combinations with cereals (e.g., maize^[37–39]), vegetables (e.g., cabbage^[40,41], cucumbers^[42,43], potatoes^[44–46] and watermelons^[47]), and green manure crops^[48–50]. Sugarcane intercropping requires advanced agronomic techniques. One common strategy is alternating wide and narrow planting rows, with intercrops sown in the wider rows^[51,52]. This approach optimizes spatial use by incorporating crops including maize, green manure and fodder plants. Another method involves ridge and furrow planting, where intercrops are grown on the ridges and sugarcane is planted in the furrows. This layout ensures uniform crop distribution, optimizes light use, and reduces competition between the main crop and intercrops, resulting in higher yields for both^[53]. Also, sugarcane intercropping demands careful management and substantial inputs of fertilizers and water. Therefore, precise agronomic practices are crucial for achieving stable, high yields. These practices include thorough land preparation, selection of high-quality seeds, timely sowing, use of plastic mulch, and integrated water and fertilizer management^[54–56]. These measures are critical for maximizing economic returns and optimizing land-use efficiency. As agricultural technology advances, the sugarcane intercropping model will be further refined to address challenges related to climate change and limited land resources.

2.3 Importance of sugarcane intercropping in promoting soil health and enhancing ecosystem services

Maintaining healthy soil is essential for improving arable land productivity and is the foundation of high-quality modern agricultural development^[57,58]. In a narrow sense, soil health refers to the biological capacity of soil to support plant growth,

particularly by managing soilborne pathogens. Broadly, soil health includes the capacity of soil to sustain long-term productivity, maintain clean water and air, and support the health of plants, animals and humans in both natural and managed ecosystems. This broader perspective highlights the importance of soil as a natural resource, emphasizing its environmental functions and ecosystem services. The ecosystem services provided by healthy soil are crucial for maintaining ecosystem productivity, biodiversity, and environmental quality^[59,60]. Sugarcane intercropping is vital for improving soil health and enhancing ecosystem services at both temporal and spatial scales, within a soil-crop-environment framework. Strategically incorporating legumes and annual or perennial cover crops into the intercropping system enhances the diversity and stability of agricultural ecosystems, improving resource use efficiency and overall productivity. This approach enriches soil fertility, reduces soilborne pathogens, and strengthens the overall functionality of the farmland ecosystem^[22,61,62]. In intercropping systems (Fig. 1), increased aboveground biodiversity supports belowground biodiversity, positively impacting soil fertility. Including legumes, known for their soil-enriching properties, significantly boosts organic matter input through root systems, increasing soil organic carbon storage and enhancing biological nitrogen fixation^[63–65]. Also, sugarcane intercropping fosters

interspecies cooperation, diversifies soil microorganisms, and improves nutrient uptake balance, nutrient use efficiency and soil structure^[32,66,67]. This balance in biological diversity helps reduce pest and disease incidence, promotes soil health and increases overall system productivity^[68].

3 Sugarcane intercropping improves soil physical properties

Soil physical properties are fundamental for supporting healthy root growth and ensuring stable, high crop yields (Fig. 2). Sugarcane intercropping enhances soil physical properties through two main mechanisms. First, the varying root structures and depths of different crops improve soil structure. Second, incorporating crop residues, either directly into the soil or as mulch, further improves soil physical properties. Su et al.^[32] found that two consecutive years of sugarcane intercropped with green manure (mung bean) significantly increased the content of mechanically stable aggregates in the 1–2 and 0.5–1 mm ranges, and water-stable aggregates in the 0.25–1, 1–2 and 2–5 mm ranges, while reducing aggregates smaller than 0.25 mm. Also, the percentage of disrupted aggregates > 0.25 mm decreased by 8.60%–16.4%, soil bulk

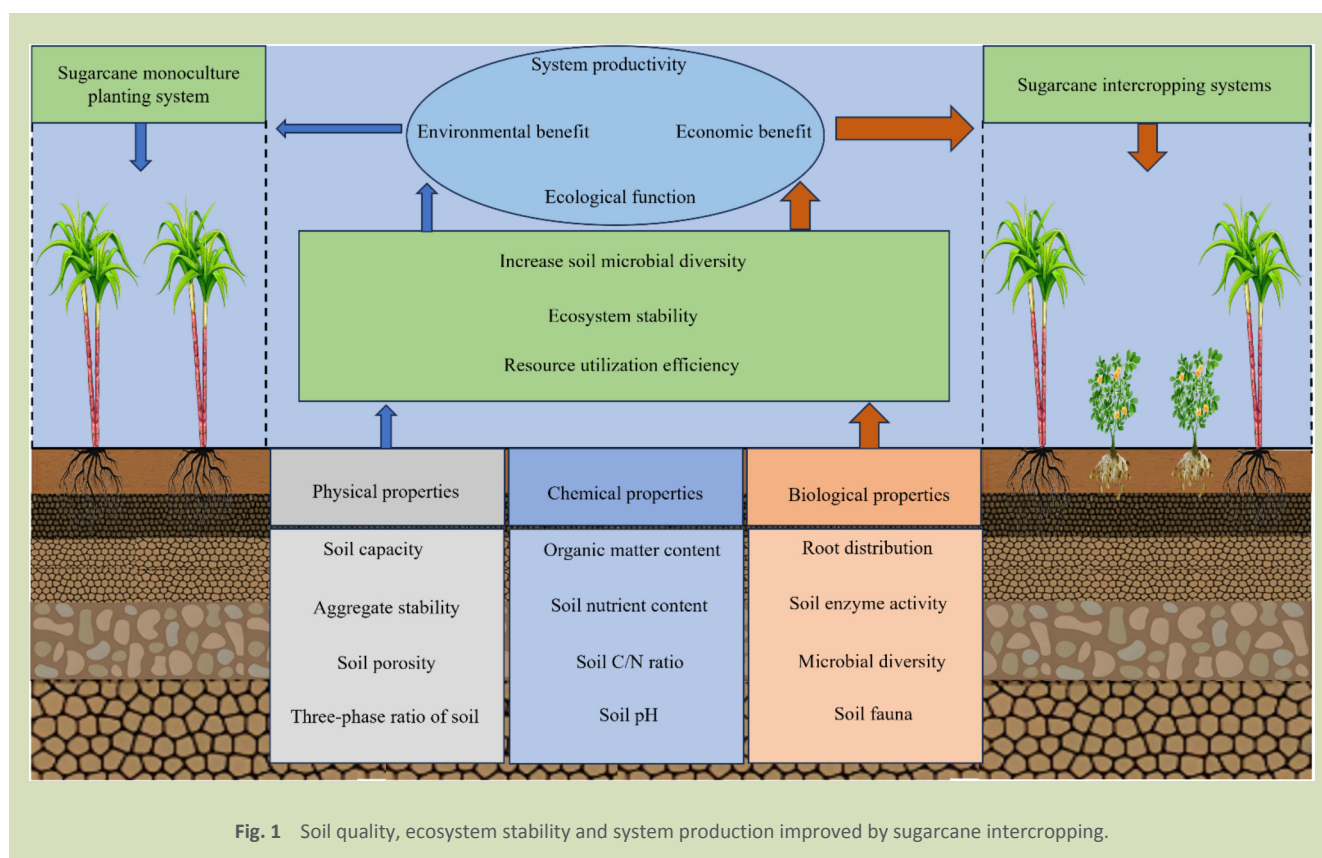
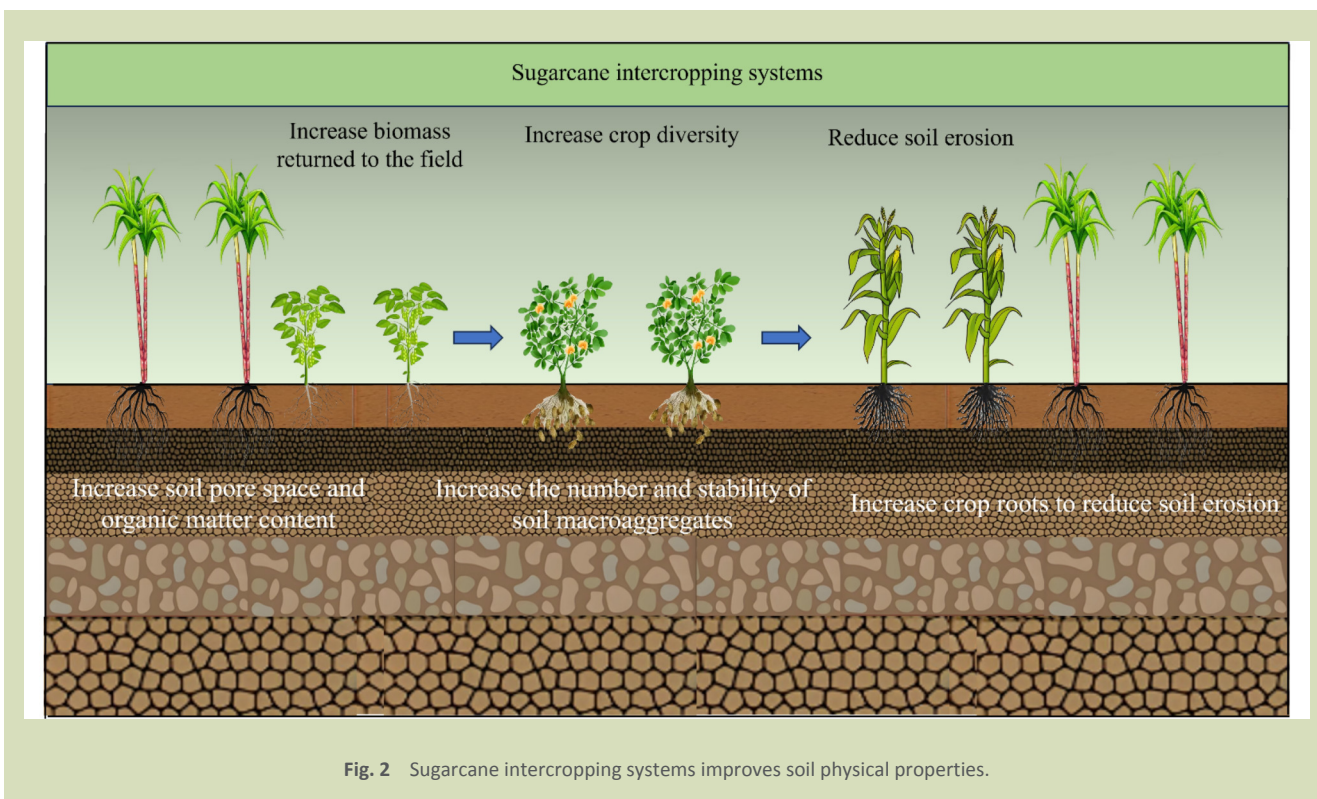


Fig. 1 Soil quality, ecosystem stability and system production improved by sugarcane intercropping.



density dropped by 2.86%–10.8%, total porosity increased by 3.65%–13.5%, and capillary porosity rose by 26.47%–41.75%. The ratio of capillary to total porosity increased by 20.4%–32.6%. Liu et al.^[69] found that intercropping sugarcane with potatoes significantly reduced soil bulk density and increased soil water content compared to monoculture.

Including deep-rooted legumes and cover crops in intercropping systems can create biopores (root channels), reduce resistance to root growth and enhance the supply of oxygen and nutrients, thereby improving soil structure^[70]. Studies indicate that increased agroecosystem productivity in intercropping systems is closely linked to root distribution and density^[71]. In contrast to monocropping, the morphological diversity of crop roots in intercropping systems contributes to biopore formation through biological tillage, loosening the soil and improving its structure. This not only reduces resistance to root penetration but also regulates the supply of water and nutrients, allowing biopores to store substantial amounts of water and nutrients, facilitating the absorption and utilization of deep soil resources^[72,73]. Also, Sugarcane intercropping systems typically generate higher aboveground biomass, which increases the organic matter returned to the soil. The inclusion of legumes and cover crops is particularly effective in reducing surface runoff, trapping sediments and minimizing soil erosion, which are crucial for soil and water conservation in the sloping farmlands of the hilly regions of southern China^[74].

4 Sugarcane intercropping improves soil chemistry properties

Soil chemical properties are crucial determinants of soil fertility, directly affecting crop growth, development, and yield. The availability of soil nutrients is essential for crop health and productivity. Qiu et al.^[75] examined the effects of sugarcane-peanut intercropping on root physiology and rhizosphere soil nutrients. They found that intercropped sugarcane roots secreted significantly higher levels of total amino acids and sugars in their exudates compared to monoculture systems.

Similarly, peanut roots in intercropped systems secreted more total sugar than those in monoculture. The rhizosphere soil of intercropped sugarcane showed significantly elevated levels of alkali-hydrolyzed nitrogen, available phosphorus (AP), available potassium (AK), and soil organic matter relative to monoculture sugarcane. However, intercropping reduced AP, AK and pH levels in peanut rhizosphere soil, indicating a more pronounced advantage for sugarcane in this intercropping system. Liu et al.^[69] reported that in a sugarcane-potato intercropping system, organic matter, hydrolyzed nitrogen, AP and AK contents were significantly increased in both rhizosphere and non-rhizosphere soils of sugarcane compared to monoculture.

Additionally, Tang et al.^[72] found that sugarcane-peanut intercropping had a more substantial impact on nutrient content in the 0–40 cm soil layer, with lesser effects observed in the 40–60 cm layer. In particular, the 0–20 cm layer of intercropped peanut soil contained significantly higher levels of available nitrogen and organic matter than monoculture peanuts, while the 20–40 cm layer of intercropped sugarcane soil had higher levels of total phosphorus and total potassium compared to monoculture sugarcane. Su et al.^[32] found that under varying fertilization conditions, intercropping and incorporating fresh mung bean stems as green manure at 16–18 t·ha⁻¹ could effectively increase nitrogen, phosphorus, potassium and organic matter contents in sugarcane soil. Increases in available nitrogen, phosphorus, and potassium ranged from 8.84% to 32.1%, 1.3% to 35.6% and 17.1% to 37.1%, respectively, while organic matter content increased by 14.0%–23.2%. Total nitrogen, phosphorus and potassium contents also increased by 7.5%–5.3%, 5.7%–16.8% and 3.6%–19.8%, respectively.

5 Sugarcane intercropping improves soil biodiversity

Soil biodiversity is a vital indicator of soil health in arable lands and is intricately linked to aboveground biodiversity^[76].

Effective agricultural management practices and cropping systems can regulate beneficial microbial communities, thereby enhancing agricultural productivity^[77,78]. For example, practices such as crop intercropping, relay intercropping and mixed cropping can modulate soil microbial diversity and functions, leading to increased crop productivity (Fig. 3).

5.1 Soil microbial diversity

Long-term monoculture often leads to a significant decline in soil microbial biomass, changes in microbial diversity and imbalances in community structure. In contrast, intercropping systems can enhance soil multifunctionality and microbial diversity. Studies have shown that, compared to monocultures of sugarcane and peanuts, sugarcane-peanut intercropping increases the numbers of bacteria, fungi and actinomycetes in the rhizosphere of both crops^[79,80]. Tang et al.^[72] found that in a sugarcane-soybean intercropping system, microbial biomass nitrogen, fungal and actinomycete populations in the 0–20 cm layer of intercropped peanut soil, and bacterial, actinomycete and total microbial quantities, and microbial biomass nitrogen content in intercropped sugarcane soil were higher than in monoculture systems. Diversified cropping systems influence soil multifunctionality by altering bacterial species richness and community composition, thereby guiding the differentiation of

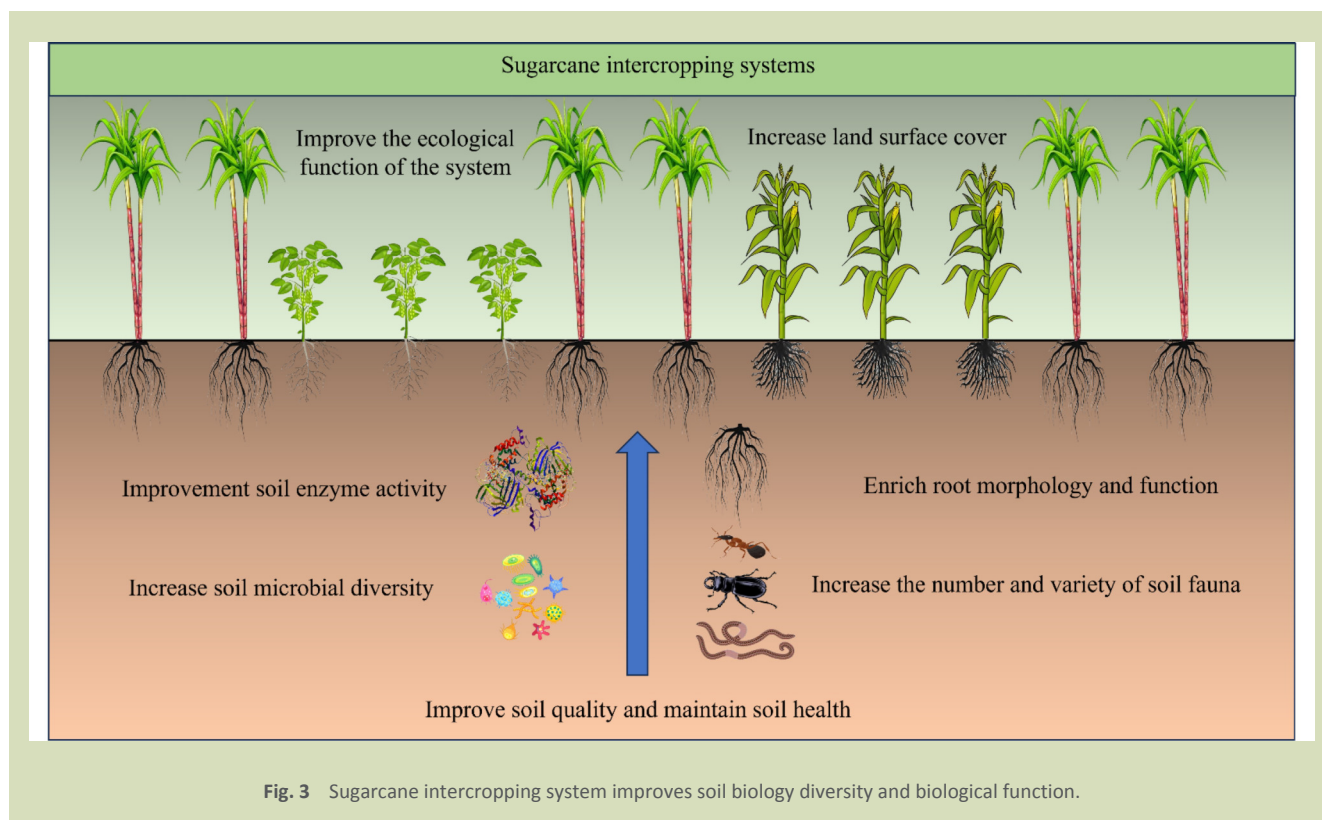


Fig. 3 Sugarcane intercropping system improves soil biology diversity and biological function.

microbial communities^[81,82]. Zheng et al.^[83] confirmed the role of intercropping in affecting the metabolic and functional relationships of rhizosphere soil microorganisms. Specifically, sugarcane intercropped with maize increased the metabolic functional diversity indices of soil microorganisms, including Shannon diversity index, Simpson index, McIntosh index, Shannon evenness index and McIntosh evenness index by 10.6%, 48.4%, 43.4%, 0.2%, and 1.7%, respectively, compared with monoculture sugarcane. This suggests that sugarcane intercropped with maize enhances the diversity and activity of rhizosphere microorganisms and alters their metabolic functions. Peng^[84] found that intercropping soybeans disrupted the community composition and structure of bacteria and nitrogen-fixing bacteria in sugarcane rhizosphere soil, significantly increasing their diversity.

5.2 Soil enzyme activity

Soil enzyme activity is a key indicator of soil biological function. Primary sources of soil enzymes include plant root exudates, soil microorganisms and plant and animal residues. In sugarcane intercropping systems, root characteristics, nutrient consumption and microbial activity vary spatially and temporally, creating complex relationships between soil enzyme activity, nutrients, the rhizosphere environment and microorganisms^[85–87]. Tang et al.^[72] found that sugarcane-peanut intercropping significantly increased protease activity in the 0–40 cm soil layer and sucrase activity in the 40–60 cm soil layer of the peanut rhizosphere, while reducing sucrase activity in the sugarcane rhizosphere. Pang et al.^[79] found that compared to monocultures of sugarcane and peanuts, sugarcane-peanut intercropping increased urease, acid phosphatase and catalase activities in the rhizosphere soil, with significant positive correlations between microbial quantity and enzyme activity. Li et al.^[88] also showed that at the peanut flowering stage, urease and phosphatase activities in the rhizosphere soil of intercropped crops increased by 59.0% and 30.0%, respectively, compared to monoculture sugarcane, and by 62.7% and 27.5%, respectively, compared to monoculture peanuts. Additionally, Hong^[89] found that intercropping soybeans with sugarcane significantly increased sucrase activity during the seedling and tillering stages. Sucrase activity was similar across all treatments during the elongation and maturity stages.

5.3 Soil fauna

Soil fauna are integral to soil biodiversity, being essential for maintaining soil health and ecosystem functions^[90]. The

structure and diversity of soil fauna are closely linked to changes in soil physical, chemical, and microbial properties. Soil fauna, through feeding and non-feeding activities, influence microbial populations and their biochemical processes, thereby affecting soil fertility^[91]. Soil fauna serve as reliable indicators of changes in soil health. Intercropping systems can increase soil fauna diversity and density, thereby improving soil fertility^[92–95]. Zhao et al.^[96] found that maize-soybean intercropping increased the number of phytophagous soil macrofauna at maturity and the number of predatory and saprophagous soil macrofauna at the jointing stage compared to monoculture. The number of phytophagous and saprophagous macrofauna increased with maize growth, while predatory macrofauna also showed an increasing trend throughout the maize growth period. Wang^[97] found that intercropping oats with soybeans, adzuki beans, potatoes and sweet potatoes increased the abundance of bacterivorous and fungivorous nematodes while reducing plant parasitic nematodes. Additionally, suitable sugarcane intercropping strategies can enhance soil fauna diversity^[98]. Soil protozoa can alter the physical structure and chemical properties of soil through their activities and secretions. For example, earthworms and termites modify soil structure by burrowing, creating biopores that enhance soil aeration and influence the distribution of organic matter and humus formation^[99]. Protozoa also influence soil microbial community structure by consuming bacteria or fungi, thus controlling pathogenic microbial communities and affecting soil organic matter decomposition. This, in turn, affects nutrient cycling and plant growth^[100]. Developing sugarcane intercropping systems can alter the structure and function of soil pathogenic microbial communities, helping control soilborne pathogens and maintain soil health.

6 Future research directions and perspective

Designing diverse and resilient sugarcane intercropping systems to enhance soil quality requires the application of ecological principles and the promotion of beneficial crop interactions. Integrating agricultural machinery and techniques into these systems is essential for improving productivity and maximizing the role of intercropping in enhancing soil and land quality. Challenges persist in areas such as theoretical frameworks, the integration of machinery with agronomy, context-specific intercropping models and policy support. Future research should focus on optimizing these areas to enhance soil health and agricultural productivity.

6.1 Developing multifunctional intercropping systems for sugarcane production

Integrating intercropping, relay intercropping, and mixed intercropping maximizes the nitrogen fixation potential of legumes, enriching the soil. Introducing legumes and green manure into sugarcane intercropping systems creates sustainable practices that balance resource use and soil fertility. To ensure stable, high yields, it is essential to optimize planting structures and develop efficient, multifunctional intercropping models designed for specific regions, such as sugarcane-soybean and sugarcane-green manure intercropping. These systems enhance soybean income or provide soil fertilization with green manure while maintaining stable sugarcane yields. Additionally, optimizing cropping structures based on resource complementarity and interspecies mutualism can help establish a green, low-carbon sugarcane intercropping system, reducing inputs, improving soil quality and increasing yields.

6.2 Improving the theoretical framework for enhancing arable land quality through sugarcane intercropping

Future research should focus on ecological principles related to biodiversity, nutrient cycling, regulation and ecosystem services in diverse sugarcane intercropping systems. A comprehensive theoretical framework can be developed by integrating knowledge from soil, crop and ecological sciences to clarify the interactions and regulation among soil, crops and the environment in intercropping systems. This includes principles such as integrated control of crop-soil-root system in new agricultural systems, multiscale ecological multifunctionality, environmental response mechanisms and biodiversity-driven soil quality evolution. Region-specific theoretical support systems should be developed to enhance soil quality through sugarcane intercropping in southern China, fostering regional agricultural green development.

6.3 Establishing a cropping technology system adapted to modern agricultural development

Intercropping systems must align with China's goals for green, sustainable and intensive agriculture. This requires selecting suitable crop cultivars or combinations for intercropping, considering ecological, agronomic and economic factors. Key technologies integrating machinery and agronomy must be developed, such as the use of integrated sugarcane planting and mulching machines with drip irrigation and fertilization systems, along with green pest and weed management

technologies. The integration of mechanized equipment, such as automated sugarcane harvesters, is also essential. Improving the efficiency of intercropping systems while ensuring sustainable land use will help establish a diversified planting technology system that minimizes resource inputs, is environmentally friendly, and ensures high and stable yields.

6.4 Applicability and promotion strategies of intercropping systems

Given the widespread use and diversity of intercropping systems across China, it is crucial to expand their role in promoting sustainable agriculture, tailored to regional conditions. This requires top-level design, policy guidance and increased awareness of the role of diversified cropping in improving soil quality, enhancing ecological services and ensuring food security. Strengthened policy and financial support is needed for areas such as agricultural planning, crop structure adjustment, and technological innovation. Developing region-specific, specialized, and multifunctional intercropping models is crucial for creating comprehensive technical solutions and promotion strategies throughout the production process. In favorable regions, efforts should focus on accelerating the development, demonstration and adoption of intercropping technologies to increase farmer participation.

7 Conclusions

Sugarcane intercropping offers significant potential for enhancing soil health and ecological system services in the hilly agricultural regions of southern China. Strategic selection of crop species and planting methods in intercropping improves soil physical properties, such as structure and porosity, while enhancing soil fertility and microbial diversity. These improvements increase agricultural productivity and stability, reduce pest and disease incidence, and mitigate soil degradation associated with long-term monoculture practices. This study emphasizes the effectiveness of sugarcane intercropping as a sustainable agricultural practice, offering a scientific basis and practical guidance for soil health management in southern Chinese agriculture. Future research should focus on optimizing intercropping patterns, integrating technologies such as water-fertilizer integration, and investigating their adaptability under different climatic conditions, as well as assessing their long-term impacts on soil health to improve and expand the applicability of this technology.

Acknowledgements

This work was funded by the Guangxi Key Research and Development Program Project (Gui Ke AB22035057, AB23026021), 2023 Water Conservancy Talent Development Funding Project (Water Conservancy Youth Science and Technology Talent Funding Project, No. JHQB202225), and the Jiangxi Provincial Postgraduate Innovation Special Fund Project (YC2023-B132).

Compliance with ethics guidelines

Wenlong Zhang, Jinhua Shao, Kai Huang, Limin Chen, Guanghui Niu, Benhui Wei, and Guoqin Huang declare that they have no conflict of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Lan Y, Xu B J, Huan Y Z, Gou J H, Liu X J, Han J W, Li K R. Food security and land use under sustainable development goals: insights from food supply to demand side and limited arable land in China. *Foods*, 2023, **12**(22): 4168
2. Tian S Z, Guan X L, Ning T Y, Sun T, Zhang Y F, Bian W F, Dong L, Gao X H. Improvement cultivated land quality by diversified cropping system: advances and prospects. *Acta Pedologica Sinica*, 2024, **61**(3): 619–634 (in Chinese)
3. Zhao J. Research on the impacts of residents' consumption structure changes on environment in China. Dissertation for the Master Degree. Chongqing, China: *Southwest University of Finance and Economics*, 2021 (in Chinese)
4. Liu X B, Zhang X Y, Wang Y X, Sui Y Y, Zhang S L, Herbert S L, Ding G, He J, Zhang L. Soil degradation: a problem threatening the sustainable development of agriculture in Northeast China. *Plant, Soil and Environment*, 2010, **56**(2): 87–97
5. Yao C L, Li Z X, Wang Y J, Zhang F, Xia B F, Wang L. Redefining the modified water benefit-based ecological index to evaluate the impact of cropland expansion on the ecological environment in an arid area. *Journal of Cleaner Production*, 2024, **477**: 143730
6. Ju X T, Kou C L, Christie P, Dou Z X, Zhang F S. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environmental Pollution*, 2007, **145**(2): 497–506
7. Zhu J H, Li X L, Christie P, Li L J. Environmental implications of low nitrogen use efficiency in excessively fertilized hot pepper (*Capsicum frutescens* L.) cropping systems. *Agriculture, Ecosystems & Environment*, 2005, **111**(1–4): 70–80
8. Yu S X, Bai X, Zhao J S, Zeng Y, Wang Y B, Wang Z, Wang L, Shi Z H. Mismatch between provincial grain production and consumption increased cropland soil erosion in China. *Agriculture, Ecosystems & Environment*, 2024, **367**: 108999
9. Huang J F, Khan M T, Perecin D, Coelho S T, Zhang M Q. Sugarcane for bioethanol production: potential of bagasse in Chinese perspective. *Renewable & Sustainable Energy Reviews*, 2020, **133**(12): 110296
10. Liu H F, Wang Y C, Cai T Y, He K, Tian X S, Chen Z, Yin Z L, Cui Z L. Integrated management to achieve synergy in sugarcane production and quality in China. *Field Crops Research*, 2024, **317**: 109552
11. Mi C R, Zu Q, He L, Huettmann F, Jin N, Li J. Climate change would enlarge suitable planting areas of sugarcane in China. *International Journal of Plant Production*, 2017, **11**(1): 151–165
12. Li Y R, Song X P, Wu J M, Li C N, Liang Q, Liu X H, Wang W Z, Tan H W, Yang L T. Sugar industry and improved sugarcane farming technologies in China. *Sugar Tech*, 2016, **18**(6): 603–611
13. Waclawovsky A J, Sato P M, Lembke C G, Moore P H, Souza G M. Sugarcane for bioenergy production: an assessment of yield and regulation of sucrose content. *Plant Biotechnology Journal*, 2010, **8**(3): 263–276
14. Ojo-kupoluyi O J, Dele-Afolabi T T, Tahir S M. Harnessing sugarcane bagasse for bioenergy production: current status, optimization, and future directions. *Sustainable Energy Technologies and Assessments*, 2024, **72**: 104074
15. Guga S, Ma Y N, Riao D, Zhi F, Xu J, Zhang J Q. Drought monitoring of sugarcane and dynamic variation characteristics under global warming: a case study of Guangxi, China. *Agricultural Water Management*, 2023, **275**(7584): 108035
16. Zhang W L. Effects of cumin/maize on crop growth, water use and economic benefits in Yanqi Basin. Dissertation for the Master Degree. Shihezi, China: *Shihezi University*, 2021 (in Chinese)
17. Viguier L, Cavan N, Bockstaller C, Cadoux S, Corre-Hellou G, Dubois S, Duval R, Keichinger O, Toqué C, De Cordoue A L T, Angevin F. Combining diversification practices to enhance

- the sustainability of conventional cropping systems. *European Journal of Agronomy*, 2021, **127**: 126279
18. Singh S R, Yadav P, Singh D, Shukla S K, Tripathi M K, Bahadur L, Mishra A, Kumar S. Intercropping in sugarcane improves functional diversity, soil quality and crop productivity. *Sugar Tech*, 2021, **23**(4): 794–810
 19. Shukla S K, Sharma L, Jaiswal V P, Dwivedi A P, Yadav S K, Pathak A D. Diversification options in sugarcane-based cropping systems for doubling farmers' income in Subtropical India. *Sugar Tech*, 2022, **24**(4): 1212–1229
 20. Nayak H S, Mkondiwa M, Patra K, Sarkar A, Reddy K S, Kumar P, Bharadwaj S, Singh R, Parihar C M. Risk-return trade-offs in diversified cropping systems under conservation agriculture: evidence from a 14-year long-term field experiment in north-western India. *European Journal of Agronomy*, 2025, **162**(5): 127436
 21. Alletto L, Vandewalle A, Debaeke P. Crop diversification improves cropping system sustainability: an 8-year on-farm experiment in South-Western France. *Agricultural Systems*, 2022, **200**: 103433
 22. Li L. Intercropping enhances agroecosystem services and functioning: current knowledge and perspectives. *Chinese Journal of Eco-Agriculture*, 2016, **24**(4): 403–415 (in Chinese)
 23. Zhang F S, Li L. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant and Soil*, 2003, **248**(1/2): 305–312
 24. Xiao Y B, Li L, Zhang F S. Effect of root contact on interspecific competition and N transfer between wheat and fababean using direct and indirect ¹⁵N techniques. *Plant and Soil*, 2004, **262**(1/2): 45–54
 25. Sun T, Li Z Z, Wu Q, Sheng T T, Du M Y. Effects of alfalfa intercropping on crop yield, water use efficiency, and overall economic benefit in the Corn Belt of Northeast China. *Field Crops Research*, 2018, **216**: 109–119
 26. Zhang Q, Liu M, Xu X L, Gunina A. Species-specific interaction affects organic nitrogen uptake during intercropping of four important crop species: a useful index for selecting appropriate intercropping combination. *Rhizosphere*, 2022, **21**: 100460
 27. Lian T X, Mu Y H, Ma Q B, Cheng Y B, Gao R, Cai Z D, Jiang B, Nian H. Use of sugarcane–soybean intercropping in acid soil impacts the structure of the soil fungal community. *Scientific Reports*, 2018, **8**(1): 14488
 28. Viaud P, Heuclin B, Letourmy P, Christina M, Versini A, Mansuy A, Chetty J, Naudin K. Sugarcane yield response to legume intercropped: a meta-analysis. *Field Crops Research*, 2023, **295**: 108882
 29. Wang X L, Feng Y J, Yu L L, Shu Y H, Tan F X, Gou Y G, Luo S S, Yang W T, Li Z X, Wang J W. Sugarcane/soybean intercropping with reduced nitrogen input improves crop productivity and reduces carbon footprint in China. *Science of the Total Environment*, 2020, **719**: 137517
 30. Raza M A, Din A M U, Gul H, Wang Z Q, Yasin H S, Khalid M H B, Iqbal N, Saeed A, Bukhari B, Al Dosary M A, Chen J, Liang X, Luo S L, Van Der Werf W, Feng Y, Qin R J, Ma Z M. Sugarcane/soybean intercropping enhances crop productivity, nutrient uptake, and net economic return with reduced inputs. *Field Crops Research*, 2024, **314**: 109428
 31. Luo S S, Yu L L, Liu Y, Zhang Y, Yang W T, Li Z X, Wang J W. Effects of reduced nitrogen input on productivity and N₂O emissions in a sugarcane/soybean intercropping system. *European Journal of Agronomy*, 2016, **81**: 78–85
 32. Su L R. Effect of mung bean intercropping and returning as green manure on sugarcane growth and field soil. Dissertation for the Doctoral Degree. Nanning, China: *Guangxi University*, 2018 (in Chinese)
 33. Mao L Y, Li H B, Gui Y Y, Zhang R H, Yang R Z, Zhou H, Wei J J, Liu X H. Effects of intercropping with *Mucuna pruriens* var. *utilis* on sugarcane rhizosphere microbe based on high throughput sequencing. *Journal of Southern Agriculture*, 2021, **52**(2): 332–340 (in Chinese)
 34. Peng J Y, Qu H P, Zhou L Q, Huang J S, Xie R L, Zhu X H, Ceng Y, Tan H W, Liu J Y. Effects of sugarcane intercropped with *Mucuna pruriens* on soil, water, nitrogen and phosphorus loss. *Jiangsu Agricultural Sciences*, 2023, **51**(9): 234–240 (in Chinese)
 35. Shen X F, Zhao Z H, Chen Y. Effects of intercropping with peanut and silicon application on sugarcane growth, yield and quality. *Sugar Tech*, 2019, **21**(3): 437–443
 36. Tang X M, Zhang Y X, Jiang J, Meng X Z, Huang Z P, Wu H N, He L Q, Xiong F Q, Liu J, Zhong R C, Han Z Q, Trang R H. Sugarcane/peanut intercropping system improves physicochemical properties by changing N and P cycling and organic matter turnover in root zone soil. *PeerJ*, 2021, **9**: e10880
 37. Wallace J S, Batchelor C H, Dabeasing D N, Teeluck M, Soopramanien G C. A comparison of the light interception and water use of plant and first ratoon sugar cane intercropped with maize. *Agricultural and Forest Meteorology*, 1991, **57**(1–3): 85–105
 38. Govinden N, Arnason J T. The relative importance of competition for water and for light in intercropping of sugar cane with maize. *Agricultural Water Management*, 1990, **17**(1–3): 233
 39. Pillay A R, Mamet J R. Intercropping sugarcane with maize. *Experimental Agriculture*, 1978, **14**(2): 161–165
 40. Singh S, Singh P, Rai R, Pathak A. Vegetables intercropping with autumn planted sugarcane. *Indian Farming*, 2018, **68**(1): 65–68
 41. Kaur N, Bhullar M S, Gill G. Weed management options for sugarcane-vegetable intercropping systems in north-western India. *Crop Protection*, 2015, **74**: 18–23
 42. Kongawad B, Patil V, Jambagi A. Intercropping studies in pre-seasonal and seasonal sugarcane. *Journal of Sugarcane Research*, 2019, **9**(1): 90328
 43. Mohammadi N K, Pankhaniya R. A review on intercropping in sugarcane. *Trends BioScience*, 2017, **10**(20): 3737–3739

44. Imam S A, Hossain A H M D, Sikka L C, Midmore D J. Agronomic management of potato/sugarcane intercropping and its economic implications. *Field Crops Research*, 1990, **25**(1–2): 111–122
45. Verma R, Yadav R. Growth and yield of sugarcane and potato in companion cropping system. *Journal of Agricultural Science*, 1986, **107**(1): 125–131
46. Gupta R, Singh P R, Singh A K. Development of sugarcane-cum-potato planter for mechanisation of simultaneous planting of sugarcane and potato. *Sugar Tech*, 2017, **19**(5): 517–525
47. Su T, Chen Y, Su L, Li Q, Qin F, He T, Li Z. Benefit of interplanting sugarcane with watermelon and soybean. *Agricultural Science and Technology*, 2017, **18**(8): 1391–1395
48. Mo Z H, Xie J L, Lin L, Li C N, Tan N, Pan H C, Huang Y S, Chen R F, Mo S P. Effects of reduced nitrogen fertilization and intercropping legume returning as green manure on sugarcane agronomic characters, yield and quality. *Modern Agricultural Science and Technology*, 2023, **20**: 38–42, 46 (in Chinese)
49. Zhou L Z, Huang Y L, Zhou J, Shen Z Y, Li Y Y, Wang F, Li S P, Zhang X, Lao C Y, Wei B H. Effects of Fenlong tillage and green manure returning on soil microbial community functional diversity at different developmental stages of sugarcane. *Southwest China Journal of Agricultural Sciences*, 2023, **36**(12): 2640–2650 (in Chinese)
50. Liu P F, Li X Y, Zhang Z X, Luo K, Lei Z Y. Effects of green manures on sugarcane yield and drought resistance. *Guizhou Agricultural Sciences*, 2015, **43**(9): 35–37, 41 (in Chinese)
51. He H L, Wei H Q, Jiang Q M, Tang R H, Wang Z T, Liao W W, Luo S S, Peng C, Guo Q, Bi D J, Tang L Q. Effects of sugarcane intercropping peanut under wide-narrow row spacing on the yield, quality and economic benefit of sugarcane. *China Tropical Agriculture*, 2021, **6**: 55–58 (in Chinese)
52. Xu W G, Huang T X, Yan S, Zhang X M, Xie W J, Zhang L, Lv H B, Yang Q H, Guo H C. Ratoon sugarcane intercropping with potato in wide-narrow row cultivation technique. *Chinese Journal of Tropical Crops*, 2015, **36**(2): 258–262 (in Chinese)
53. Li J C. Study on adaptation of sugarcane in different line spacing to intercropping of spring soybean under mechanical planting. Dissertation for the Master Degree. Nanning, China: *Guangxi University*, 2017
54. Kaushal A, Patole R, Singh K G. Drip irrigation in sugarcane: a review. *Agricultural Reviews*, 2012, **33**(3): 211–219
55. Surendran U, Jayakumar M, Marimuthu S. Low cost drip irrigation: impact on sugarcane yield, water and energy saving in semiarid tropical agroecosystem in India. *Science of the Total Environment*, 2016, **573**: 1430–1440
56. Wiedenfeld B. Scheduling water application on drip irrigated sugarcane. *Agricultural Water Management*, 2004, **64**(2): 169–181
57. Zhang J L, Zhang J Z, Shen J B, Tian J, Jin K M, Zhang F S. Soil health and agriculture green development: opportunities and challenges. *Acta Pedologica Sinica*, 2020, **57**(4): 783–796 (in Chinese)
58. Yang X X, Zhou Q X, Wang T L. Connotation and ecological indicators of soil health and its research prospect. *Ecologic Science*, 2007, **26**(4): 374–380 (in Chinese)
59. Xu M G, Duan Y H, Bai S S, Zhang W J, Sun N. Research and prospects for soil health based on long-term experiments in arable land of China. *Plant Nutrition and Fertilizer Science*, 2024, **30**(7): 1253–1261 (in Chinese)
60. Si S C, Wu Y C, Li Y, Tu C, Fu C C, Luo Y M. The current research progress and prospects of cultivated and grassland soil health—A review. *Acta Pedologica Sinica*, 2022, **59**(3): 625–642 (in Chinese)
61. Su B Y, Chen S B, Li Y G, Yang W Y. Intercropping enhances the farmland ecosystem services. *Acta Ecologica Sinica*, 2013, **33**(14): 4505–4514 (in Chinese)
62. Ye Y L. Effect of intercropping on nitrogen and water use. Dissertation for the Doctoral Degree. Beijing: *China Agricultural University*, 2003 (in Chinese)
63. He H M, Liu L N, Munir S, Bashir N H, Yi W, Jing Y, Li C Y. Crop diversity and pest management in sustainable agriculture. *Journal of Integrative Agriculture*, 2019, **18**(9): 1945–1952
64. Yang J B. Effects of intercropping with soybean on growth of sugarcane and diversities of endophytic bacteria and endophytic nitrogen-fixing bacteria. Dissertation for the Doctoral Degree. Nanning, China: *Guangxi University*, 2018 (in Chinese)
65. Xu X. Effects of nitrogen reduction on yield stability and gene structure of nitrogen cycling function in sugarcane//soybean intercropping system. Dissertation for the Master Degree. Guangzhou, China: *South China Agricultural University*, 2020 (in Chinese)
66. Solanki M K, Wang Z, Wang F Y, Li C N, Lan T J, Singh R K, Singh P, Yang L T, Li Y R. Intercropping in sugarcane cultivation influenced the soil properties and enhanced the diversity of vital diazotrophic bacteria. *Sugar Tech*, 2017, **19**(2): 136–147
67. Suman A, Lal M, Singh A K, Gaur A. Microbial biomass turnover in Indian subtropical soils under different sugarcane intercropping systems. *Agronomy Journal*, 2006, **98**(3): 698–704
68. Kumar A, Kumar N, Chand H. General views of sugarcane based intercropping system and its impact on borer's incidence. *Biomolecule Reports*, 2020, **18**(2): 1–7
69. Liu X Y, Liang Q, Pang T, Li Y J, Xu L, Wu K Z, Deng Z N, Song X P, Li Y R, Wang W Z. Influence of mechanized cultivation on sugarcane/potato intercropping in soil microbial diversity and nutrient absorption of sugarcane. *Journal of Southern Agriculture*, 2021, **52**(2): 297–306 (in Chinese)
70. Yin W, Chai Q, Fan Z L, Hu F L, Zhao L H, Fan H, He W, Zhao C, Yu A Z, Sun Y L, Wang F. Review on physiological

- and ecological characteristics and agronomic regulatory pathways of intercropping to delay root-canopy senescence of crops. *Journal of Integrative Agriculture*, 2024, **24**(1): 1–22
71. Streit J, Meinen C, Rauber R. Intercropping effects on root distribution of eight novel winter faba bean genotypes mixed with winter wheat. *Field Crops Research*, 2019, **235**: 1–10
 72. Tang X M, Liao L L, Wu H N, Xiong J, Li Z, Huang Z P, He L Q, Jiang J, Zhong R C, Han Z Q, Tang R H. Effects of sugarcane/peanut intercropping on root exudates and rhizosphere soil nutrient. *Plants*, 2024, **13**(22): 3257
 73. Zhang F B, Hou Y X, Ao Y Y, Shen J B, Jin K M. Root-soil interaction under soil compaction. *Plant Nutrition and Fertilizer Science*, 2021, **27**(3): 531–543 (in Chinese)
 74. Liang Y T, Xu T H, Jin L F, Zhang G F, Yuan X F. Research advances of application of legumes in ecological restoration. *Journal of Anhui Agricultural Sciences*, 2014, **42**(20): 6637–6638, 6655 (in Chinese)
 75. Qiu J M, Wu H N, Huang Z P, He L Q, Li Z, Zhong R C, Han Z Q, Jiang J, Li B, Tang X M, Tang R H. Effects of sugarcane/peanut intercropping on root physiology and rhizosphere soil nutrients. *Chinese Journal of Oil Crop Sciences*, 2024, **46**(4): 889–896 (in Chinese)
 76. Duchene O, Vian J F, Celette F. Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review. *Agriculture, Ecosystems & Environment*, 2017, **240**: 148–161
 77. De Deyn G B, Van Der Putten W H. Linking aboveground and belowground diversity. *Trends in Ecology & Evolution*, 2005, **20**(11): 625–633
 78. Zhu Y G, Peng J J, Wei Z, Shen Q R, Zhang F S. Linking the soil microbiome to soil health. *Science in China (Series C)*, 2021, **51**(1): 1–11
 79. Pang Z Q, Fallah N, Weng P Y, Zhou Y M, Tang X M, Tayyab M, Liu Y M, Liu Q, Xiao Y J, Hu C H, Kan Y J, Lin W X, Yuan Z N. Sugarcane-peanut intercropping system enhances bacteria abundance, diversity, and sugarcane parameters in rhizospheric and bulk soils. *Frontiers in Microbiology*, 2022, **12**: 815129
 80. Tang X M, He Y L, Zhang Z, Wu H N, He L Q, Jiang J, Meng W W, Huang Z P, Xiong F Q, Liu J, Zhong R C, Han Z Q, Wan S B, Tang R H. Beneficial shift of rhizosphere soil nutrients and metabolites under a sugarcane/peanut intercropping system. *Frontiers in Plant Science*, 2022, **13**: 1018727
 81. Li M H, Guo J J, Ren T, Luo G W, Shen Q R, Lu J W, Guo S W, Ling N. Crop rotation history constrains soil biodiversity and multifunctionality relationships. *Agriculture, Ecosystems & Environment*, 2021, **319**: 107550
 82. Mooshammer M, Grandy A S, Calderón F, Culman S, Deen B, Drijber R A, Dunfield K, Jin V L, Lehman R M, Osborne S L, Schmer M, Bowles T M. Microbial feedbacks on soil organic matter dynamics underlying the legacy effect of diversified cropping systems. *Soil Biology & Biochemistry*, 2022, **167**: 108584
 83. Zheng Y Q, Zhang L M, Yang J C, Yang J, Gao R, Chen L X, Dong X M, Sun J H, Xiao G L, Li Z Y, Chen B. Effects of sugarcane and maize intercropping on sugarcane rhizosphere microbe metabolic function diversity. *Chinese Journal of Eco-Agriculture*, 2016, **24**(5): 618–627 (in Chinese)
 84. Peng D H. Effects of intercropping sugarcane with soybean on physical and chemical properties, diversity of bacteria and nitrogen-fixing bacteria in rhizosphere soil. Dissertation for the Master Degree. Nanning, China: *Guangxi University*, 2014 (in Chinese)
 85. Li X P, Mu Y H, Cheng Y B, Liu X G, Nian H. Effects of intercropping sugarcane and soybean on growth, rhizosphere soil microbes, nitrogen and phosphorus availability. *Acta Physiologiae Plantarum*, 2013, **35**(4): 1113–1119
 86. Daunoras J, Kačergius A, Gudukaitė R. Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*, 2024, **13**(2): 85
 87. Tang X M, Jiang J, Huang Z P, Wu H N, Wang J, He L Q, Xiong F Q, Zhong R C, Liu J, Han Z Q, Tang R H, He L F. Sugarcane/peanut intercropping system improves the soil quality and increases the abundance of beneficial microbes. *Journal of Basic Microbiology*, 2021, **61**(2): 165–176
 88. Li Y B, Shen X F, Chen Y. Inter-cultivation of peanuts and sugarcane improves aluminum stress in sugarcane and its effects on soil microorganisms and enzyme activity. In: Chinese Agricultural Society Farming System Branch 2016 Academic Annual Meeting, Urumchi. Beijing: *Chinese Agricultural Society Farming System Branch*, 2016, 48 (in Chinese)
 89. Hong D X. Effect of two different interplanting crops on the sugarcane growth and soil physical and chemical properties of cane field. Dissertation for the Master Degree. Fuzhou, China: *Fujian Agriculture and Forestry University*, 2011 (in Chinese)
 90. Kumawat A, Bamboriya S D, Meena R S, Yadav D, Kumar A, Kumar S, Raj A, Pradhan G. Legume-based inter-cropping to achieve the crop, soil, and environmental health security. In: Meena R S, Kumar S, eds. *Advances in Legumes for Sustainable Intensification*. Academic Press, 2022, **16**: 307–328
 91. Sun X, Li Q, Yao H F, Liu M Q, Wu D H, Zhu D, Zhu Y G. Soil fauna and soil health. *Acta Pedologica Sinica*, 2021, **58**(5): 1073–1083 (in Chinese)
 92. Rakotomalala A A N A, Ficiyan A M, Tschamtk T. Intercropping enhances beneficial arthropods and controls pests: a systematic review and meta-analysis. *Agriculture, Ecosystems & Environment*, 2023, **356**: 108617
 93. Brooker R W, Bennett A E, Cong W F, Daniell T J, George T S, Hallett P D, Hawes C, Iannetta P P M, Jones H G, Karley A J, Li L, McKenzie B M, Pakeman R J, Paterson E, Schöb C, Shen J, Squire G, Watson C A, Zhang C, Zhang F, Zhang J, White P J. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, 2015, **206**(1): 107–117

94. Letourneau D K, Armbrrecht I, Rivera B S, Lerma J M, Carmona E J, Daza M C, Escobar S, Galindo V, Gutiérrez C, López S D, Mejía J L, Rangel A M A, Rangel J H, Rivera L, Saavedra C A, Torres A M, Trujillo A R. Does plant diversity benefit agroecosystems? A synthetic review. *Ecological Applications*, 2011, **21**(1): 9–21
95. Russell E P. Enemies hypothesis: a review of the effect of vegetational diversity on predatory insects and parasitoids. *Environmental Entomology*, 1989, **18**(4): 590–599
96. Zhao B Y N M L, De H S, Hong M, Liu P F, Xing A, Ye H, Chang G J, Mei L. Effect of maize/soybean intercropping pattern on dynamic changes of cropland soil macrofauna community. *Soils and Fertilizers Sciences in China*, 2022, **7**: 132–140 (in Chinese)
97. Wang Y N. Effects of oat intercropping patterns on crop yield, soil properties and nematode community. Dissertation for the Master Degree. Taiyuan, China: *Shanxi Agricultural University*, 2023 (in Chinese)
98. Zhang W X, Shen Z F, Shao Y H, Shi L L, Liu S J, Shi N N, Fu S L. Soil biota and sustainable agriculture: a review. *Acta Ecologica Sinica*, 2020, **40**(10): 3183–3206 (in Chinese)
99. Oliverio A M, Geisen S, Delgado-Baquerizo M, Maestre F T, Turner B L, Fierer N. The global-scale distributions of soil protists and their contributions to belowground systems. *Science Advances*, 2020, **6**(4): eaax8787
100. Friberg H, Lagerlöf J, Rämert B. Influence of soil fauna on fungal plant pathogens in agricultural and horticultural systems. *Biocontrol Science and Technology*, 2005, **15**(7): 641–658