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Exploring the link between soil health and crop productivity

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ABSTRACT

Understanding the complex interactions of plants and soils in the face of global food security and environmental degradation challenges is critical to the future of sustainable agriculture. This review discusses the important link between soil health and crop productivity by providing and comprehensive assessment of soil properties and management methods. By examining the physical, chemical, and biological properties of soil, it uncovers the key limitations posed by the soil environment on crop growth. The review highlights how soil texture, nutrient availability, and moisture levels directly impact on root growth, water uptake, and nutrient use efficiencies, while also exploring how diverse cropping systems enhance soil ecology and biodiversity. By utilizing state-of-the-art bioinformatics, we offer an in-depth exploration of rhizosphere microbial communities, emphasizing the functions of phosphate-solubilizing and nitrogen-fixing bacteria in promoting vital nutrient cycles. The potential of using microbial fertilizers to increase crop resistance to disease and stress hold a major premise for future sustainability in agriculture. In this regard, this review highlights the long-term impacts of crop cultivation on soil microbial diversity, revealing intricate selection processes between crops and their microbial partners in shaping crop-soil-microbe interactions. In terms of soil management, practical nutrient management strategies are proposed based on soil testing, emphasizing the benefits of organic farming and conservation tillage for soil health. Modern precision agricultural tools and remote sensing technologies are encouraged to be refined for effective nutrient management. At the policy level, we evaluate international guidelines aimed at fostering agricultural sustainability, suggesting new research pathways for crop-soil dynamics and offering approaches for developing soil health indicators in the face of global environmental challenges.

1. Introduction

Sustainable agriculture is critical in addressing the growing challenges of food security, environmental degradation, and climate change. At the core of this sustainability lies the intricate relationship between soil and crops, a dynamic interaction that dictates crop productivity, soil health, and ecosystem resilience. Understanding and optimizing these crop-soil synergies is essential for enhancing agricultural production and promoting long-term sustainability.

Soil health, characterized by its physical, chemical, and biological properties, plays a foundational role in determining crop performance. Edaphic factors such as soil texture, moisture content, pH, and nutrient levels, all directly impact crop growth and development (Hu et al., 2024). Sandy soils are particularly vulnerable to drought due to their poor water retention, while acidic soils can limit the growth of certain crops (Naorem et al., 2023). Crop root systems play a vital role in enhancing soil structure, promoting the formation of soil aggregates, and improving soil aeration and water-holding capacity (Lu et al., 2020). Additionally, these root systems recruit beneficial microorganisms that help maintain the balance of the soil ecosystem (Han et al., 2021). Equally important is the role of soil biodiversity, particularly the rhizosphere microbial communities, which are vital in nutrient cycling processes like nitrogen fixation and phosphate solubilization (Saeed et al., 2021). Soil bacteria, fungi, and actinomycetes establish a symbiotic relationship with crop roots, facilitating nutrient absorption, enhancing disease resistance, and aiding in the decomposition of organic matter (Wei et al., 2024). These microorganisms not only support crop nutrition but also contribute to stress tolerance and disease resistance, providing a natural buffer against environmental stresses. This synergy between crop-soil-microbes promotes nutrient cycling and contribute to the overall soil ecosystem stability.

In addition to biological interactions, The planting method, soil tillage, and fertilization strategies of crops directly influence soil pH, organic matter content, and the characteristics of microbial

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communities (Khmelevtsova et al., 2022). Different crops have different ability to absorb and use soil nutrients. Selecting suitable crop varieties for rotation and intercropping can improve soil fertility and health (Glaze-Corcoran et al., 2020). Diverse planting methods can promote soil microbial diversity, thereby maintaining the balance and stability of the soil ecosystem (Gupta et al., 2022). Additionally, the nutrient supply, water retention, and aeration conditions within the soil significantly impact crop growth and yield (Zhang et al., 2022c). The development of crop root systems is intricately linked to the soil's structural looseness or compactness, with soil microorganisms playing a crucial regulatory role in root system growth (Sharma et al., 2021). The soil microbial community contributes to crop growth and development through the decomposition of organic matter, nitrogen fixation, and the facilitation of nutrient cycling (Yadav et al., 2021). Concurrently, root exudates secreted by crop root systems can attract soil microorganisms, fostering a symbiotic relationship that enhances microbial diversity and abundance.

Gaining a deeper understanding of the interactive relationship between crops and soil microorganisms is essential for optimizing the soil environment and enhancing crop yield. Despite the critical importance of these interactions, current research often focuses on isolated aspects such as root growth, nutrient uptake, and stress tolerance. This approach leaves a significant gap in comprehensive evaluations that integrate soil-crop dynamics into a unified framework. Unlike previous reviews that predominantly address either chemical or biological facets (Sela et al., 2024), this work explores the synergies among crop genotypes, soil properties, and microbial communities. By doing so, it reveals mutual selection mechanisms that are often overlooked. Thus, this review aims to explore the multifaceted interactions between crops and soils, focusing on how these dynamics influence soil health and agricultural sustainability. By synthesizing knowledge on microbial interactions, soil management practices, and advanced precision agriculture technologies, we provide insights into optimizing soil-crop-microbial synergies. The ultimate goal is to create resilient agricultural practices that enhance productivity, conserve soil resources, and contribute to global efforts toward sustainable development.

2. Edaphic factors regulate crop-soil synergies

2.1. Soil texture, root development and nutrient uptake

The particle composition, texture, and permeability of soil are critical determinants of its aeration, water-holding capacity, and fertility (Wei et al., 2023). Soils with excessively loose and permeable textures may hinder the establishment of a robust root system, rendering plants susceptible to environmental stresses and ultimately leading to suboptimal growth. This condition can exacerbate issues such as nutrient leaching and reduced water retention, posing significant challenges for plant development. Conversely, soils characterized by high compaction and poor permeability can result in waterlogging and hypoxia, which severely restrict root growth and function, ultimately impairing plant health and productivity (Manik et al., 2019). Moreover, soils with a softer, looser texture are often more favorable for microbial colonization. This microbial presence plays a crucial role in nutrient cycling within the rhizosphere, facilitating the release and transformation of nutrients, thereby enhancing nutrient uptake by plants (Vetterlein et al., 2020). These soils support a dynamic microbial ecosystem that contributes to the breakdown of organic matter and the production of plant growth-promoting substances. In stark contrast, excessively compact soils create unfavorable conditions for microbial proliferation. The limited pore space and reduced oxygen availability in such soils inhibit microbial activity, leading to a decline in nutrient mineralization and availability. This adversely affects the efficiency of nutrient absorption and utilization by plant roots, thereby diminishing plant growth and yield (Li et al., 2022). The interplay between soil texture, microbial activity, and root development underscores the complexity of soil-plant interactions and highlights the need for balanced soil management practices to optimize plant health and agricultural productivity.

Clayey soils, characterized by their small particle size and large surface area, exhibit a high capacity for water adsorption and retention, significantly enhancing crop water absorption and supporting robust growth (Fig. 1). This high water retention is particularly beneficial for maintaining soil moisture levels in regions with limited rainfall. However, the low permeability of clay soils can predispose them to waterlogging conditions, which results in hypoxia and increases the risk of root rot (Leotta et al., 2023). The anaerobic environment created by waterlogged clay soils impairs root respiration and nutrient uptake, severely constraining crop growth and development (Lian et al., 2023). In contrast, sandy soils are composed of coarser particles with greater inter-particle spaces, facilitating excellent drainage and high aeration. Despite these advantages, sandy soils have a limited water-holding capacity and high water mobility, leading to rapid water loss and reduced nutrient retention. This poses significant challenges for crop roots in accessing sufficient water and essential nutrients, thereby negatively impacting plant growth and development (Adhikari et al., 2022). The rapid drainage in sandy soils may also necessitate more frequent irrigation and fertilization, increasing resource use and management costs. Loamy soils, characterized by a balanced mixture of sand, silt, and clay (40–40–20 %), exhibit an optimal permeability coefficient ($K = 8.67 \times 10^{-5}$ to 3.22×10^{-5} cm/s). This balance promotes adequate water retention (up to 22 % by volume) while ensuring efficient drainage, making loamy soils particularly suitable for stabilizing water levels in rice fields and similar applications (Khanh et al., 2024). These soils are well-aerated, maintaining favorable moisture and oxygen levels that are crucial for healthy root function and overall plant growth (Wang et al., 2024a). The structure of loamy soils supports a dynamic and diverse microbial ecosystem, further enhancing nutrient cycling and availability. The balanced physical properties of loamy soils make them highly desirable for agricultural productivity, as they mitigate the extremes observed in purely clay or sandy soils (Shahane and Shivay, 2021). A nuanced understanding of soil textures highlights the significance of customized soil management practices designed to optimize water and nutrient availability, promote healthy root development, and enhance crop yields. Future research and soil conservation strategies should further investigate the interactions among soil texture, microbial activity, and plant health to develop sustainable agricultural practices.

In clay soils, crops frequently encounter challenges related to nutrient absorption due to the high cation exchange capacity (CEC) of these soils. While this property enables clay soils to adsorb and retain nutrients efficiently, it can also render these nutrients less accessible to plant roots. The dense structure of clay soils can impede root penetration, thereby limiting access to deeper soil layers where essential nutrients may be concentrated (Grzebisz et al., 2022). This limitation necessitates specific management practices aimed at enhancing nutrient bioavailability and promoting root proliferation. Conversely, sandy soils, characterized by their low CEC and high permeability, often experience nutrient leaching. The large particle size and increased porosity of sandy soils facilitate rapid water drainage, which can wash away essential nutrients before they can be absorbed by plant roots (Sale et al., 2021). This nutrient loss can lead to suboptimal plant growth and development, necessitating frequent fertilization and careful water management to maintain adequate nutrient levels within the root zone (Rosemarin et al., 2020). Silty soils, with their intermediate particle size and high water-holding capacity, can present challenges related to nutrient stagnation. The fine particles in silty soils can retain water and nutrients; however, this can also slow the release and movement of these nutrients to plant roots (Bai et al., 2022). Such stagnation can result in periods of nutrient unavailability, adversely affecting plant growth and yield (Priya et al., 2024). Effective soil management strategies are essential to balance water retention and nutrient release in silty soils. To address these challenges, specific soil management practices can be implemented. In clay soils, the application of organic fertilizers and

Fig. 1. The triangle of soil structure is determined by the ratio of sand, powder and clay.

strategic tilling can enhance soil structure, improve aeration, and reduce excessive nutrient adsorption. The organic matter derived from fertilizers can increase microbial activity and enhance soil porosity, thereby facilitating better root growth and nutrient uptake (Zhang et al., 2022d). For sandy soils, incorporating organic fertilizers and mulch can significantly boost the organic matter content, improving soil structure and water retention capacity. These practices help mitigate nutrient loss by enhancing the soil's ability to retain water and nutrients, thus providing a more stable environment for root growth and nutrient absorption (Du et al., 2022). In silty soils, the implementation of appropriate soil loosening techniques and improved drainage can enhance aeration and facilitate the timely release of nutrients. These practices help prevent waterlogging and ensure a more consistent supply of nutrients to plant roots, promoting healthier plant growth and development. Understanding the unique properties and challenges associated with different soil types is essential for developing effective soil management strategies. By employing tailored practices based on soil texture, it is possible to optimize nutrient availability, improve soil health, and enhance crop productivity.

2.2. Soil nutrients availability and crop productivity

Nitrogen (N), phosphorus (P), and potassium (K) are critical macronutrients that play indispensable roles in supporting crop growth and development. However, managing these nutrients requires careful consideration to avoid adverse effects on soil health and crop productivity. The manuscript briefly mentions soil acidification caused by excessive nitrogen fertilization but fails to explore the long-term effects on microbial diversity, nutrient release, and broader ecosystem dynamics. Soil acidification can alter the structure of microbial communities, reducing the abundance of beneficial microorganisms and disrupting nutrient cycling processes (Naz et al., 2022). Furthermore, this acidification can mobilize toxic metals such as aluminum, which can inhibit root growth and function (Baloch et al., 2024). The imbalance created by excessive N can thus have cascading effects on the entire soil ecosystem, ultimately impacting crop health and yield. P is a vital component of cellular nucleic acids, adenosine triphosphate, and phospholipids, all of which are essential for energy transfer, genetic information storage, and membrane integrity in plants. A deficiency in P can severely limit these fundamental processes, leading to stunted growth and poor root development (Bhat et al., 2024). The limited mobility of P in the soil often necessitates strategic placement and management to ensure its availability to crop roots. Moreover, the over-application of phosphorus can result in environmental issues such as eutrophication of water bodies, highlighting the need for balanced fertilization practices.

K is essential for maintaining osmotic pressure, activating enzymes, and balancing ions within crop cells. It plays a significant role in photosynthesis, protein synthesis, and stress resistance. A deficiency in potassium may manifest as chlorosis (yellowing of leaves), necrosis at the leaf edges, and overall stunted growth, which can severely impact crop yield and quality (Patel et al., 2022). Furthermore, potassium enhances water use efficiency and resistance to diseases and pests, making its adequate supply crucial for sustainable crop production. To optimize the utilization of these essential nutrients, integrated nutrient management approaches should be adopted. This includes conducting regular soil testing to monitor nutrient levels and employing precision agriculture techniques to apply the appropriate amount of nutrients at the right time. The incorporation of organic matter through compost or cover crops can improve nutrient retention and decrease reliance on synthetic fertilizers. Additionally, utilizing slow-release fertilizers and nutrient inhibitors can help mitigate leaching and runoff, ensuring that nutrients remain accessible to crops over extended periods. By comprehending the complex interactions between these macronutrients and the soil-plant system, farmers and agronomists can devise more effective nutrient management strategies. These strategies not only enhance crop productivity but also promote long-term soil health and environmental sustainability.

Excess N can promote vigorous crop growth, which can lead to increased density, decreased stem strength, and ultimately reduced yield and quality (Liu et al., 2022b). Similarly, excessive P can impede root development, adversely affecting water and nutrient absorption, which may result in water stress and nutrient deficiencies (Bechtaoui et al., 2021). Furthermore, excessive N can acidify the soil, disrupting soil structure and the balance of microbial communities, thereby impacting the overall health of the soil ecosystem. Excessive P may accumulate in the soil, affecting microbial growth and activity, reducing soil respiration, and hindering the decomposition of organic matter (Wang et al., 2024b). Additionally, an overabundance of nutrients, such as N and P, can alter the species composition and abundance of soil microorganisms, suppressing the growth of beneficial microbes while promoting the proliferation of harmful ones (Zeeshan Ul Haq et al., 2023). This imbalance can compromise the conservation and regulatory functions of the soil ecosystem. In summary, nutrient imbalance is a critical factor influencing soil health and crop growth. To mitigate issues related to nutrient imbalance, it is essential to employ scientifically informed fertilization practices, judiciously utilize organic and chemical fertilizers, and maintain a balanced soil nutrient status.

2.3. Soil moisture, drainage and crop performance

Under drought stress, crops reduce stomatal opening to decrease water transpiration and increase root surface area, thereby enhancing their water absorption capacity (Seleiman et al., 2021). Additionally, crops accumulate antioxidants to mitigate oxidative stress caused by drought, which protects cells from damage (Kerchev and Van Breusegem, 2022). Certain drought-resistant strains facilitate water absorption, promote root growth, and produce plant growth-promoting substances, thereby enhancing drought resistance in crops. Simultaneously, symbiotic strains establish mutualistic relationships with plants, supplying essential nutrients such as nitrogen and phosphorus, which help crops better cope with drought conditions.

Adopting mulching techniques effectively reduces soil water evaporation and improves water use efficiency (Table 1). Proper fertilization increases soil organic matter content, enhances soil structure, and improves the soil's capacity to retain water and nutrients (Tian et al., 2022). Selecting drought-resistant varieties and implementing an effective irrigation system are also critical measures for enhancing crop drought resistance. Drip irrigation, which precisely controls water flow, conserves 33 % more water than traditional sprinkler irrigation and 81.6 % more than furrow irrigation (Ismail et al., 2024), while also increasing yields by approximately 30 % (Geries et al., 2021). This method nearly eliminates water waste and minimizes soil evaporation loss, significantly reducing both water waste and evaporation, while simultaneously improving crop yield and quality. In the context of increasingly scarce global water resources, the promotion and application of these high-efficiency irrigation technologies are essential for the sustainable development of agriculture.

Crops with deep root systems, such as corn and wheat, are more effective at absorbing soil moisture during drought conditions, thereby enhancing their drought resistance. Short-cycle crops exhibit greater adaptability to short-term drought environments, while long-cycle crops necessitate stronger drought resistance to complete their growth cycles (Baccar et al., 2023). Additionally, crops with small leaves and dense hairs can minimize water evaporation and, consequently, water loss under drought conditions. Therefore, selecting drought-resistant varieties that are well-suited to arid environments is a crucial step towards achieving sustainable agricultural development. By considering factors such as root system structure, growth cycle, and leaf characteristics, we can more effectively select crop varieties that are adapted to drought conditions, improve crop drought resistance, and ensure the sustainability of agricultural production.

3. Crop diversity and soil health

3.1. Ecological significance of crop diversity

Crop diversity significantly influences soil health, particularly through its provision of essential ecosystem services (Fig. 2). Different plant species demonstrate varying levels of adaptability and compatibility across geographical environments. Their interactions can establish complex food chains and material cycling networks within ecosystems, thereby enhancing stability and resilience. Moreover, crop diversity improves nutrient use efficiency in the soil, reduces dependence on chemical fertilizers and pesticides, and mitigates the adverse environmental impacts of agriculture (Rebouh et al., 2023). By cultivating a variety of crops, their synergistic effects can be leveraged to enhance both the yield and quality of farmland, thus advancing sustainable agricultural development goals. Additionally, the planting of diverse vegetation promotes soil fertility and resistance, optimizes the structure of soil microbial communities, and increases soil organic carbon content, fostering a positive cycle of soil health and ecosystem well-being (Toor et al., 2021).

The introduction of various crop types in crop diversity can enhance adaptability and resistance, thereby reducing the incidence of pests and diseases. Ecological niche differentiation among crops facilitates effective utilization of soil nutrients, mitigates soil degradation, and sustains soil fertility and productivity (Sofo et al., 2022). A higher level of species diversity is associated with improved productivity, as different species fulfill distinct functions and roles within the ecosystem, forming interaction networks in their shared environment (Chen et al., 2022). Different crop types can utilize various soil nutrients, alleviating the nutrient depletion problem that arises from the long-term cultivation of the same crop on the same land (Das et al., 2022a). The complementary effects among different crops can optimize soil resource utilization, enhance nutrient use efficiency, and promote overall crop growth and development.

Crop rotation and intercropping are essential management practices

Table 1
The effects of various mulching materials on water use efficiency for different crops.

Mulching material	Crop	Water use efficiency improvement (%)	Reduction in soil water evaporation (%)	Supporting Data/Study
Straw mulch	Wheat	20–30 %	40–50 %	(Zhang et al., 2022a)
Plastic mulch (Black)	Tomato	25–35 %	50–60 %	(Zhang et al., 2022b)
Wood chips mulch	Maize	15–25 %	30–40 %	(Wang et al., 2019)
Peat mulch	Strawberry	20–28 %	35–45 %	(Hernández-Martínez et al., 2023)
Grass clippings mulch	Soybean	18–22 %	25–35 %	(El-Beltagi et al., 2022)
Bark mulch	Apple	22–30 %	38–48 %	(Zhang et al., 2021a)
Compost mulch	Carrot	15–20 %	20–30 %	(Ferreira et al., 2024)
Gravel mulch	Grapevine	10–15 %	15–25 %	(Gonzalez-Maldonado et al., 2024)
Living mulch (Cover crops)	Corn	12–18 %	25–33 %	(Moore, 2023)
Sawdust mulch	Cucumber	14–20 %	28–35 %	(El-Beltagi et al., 2022)

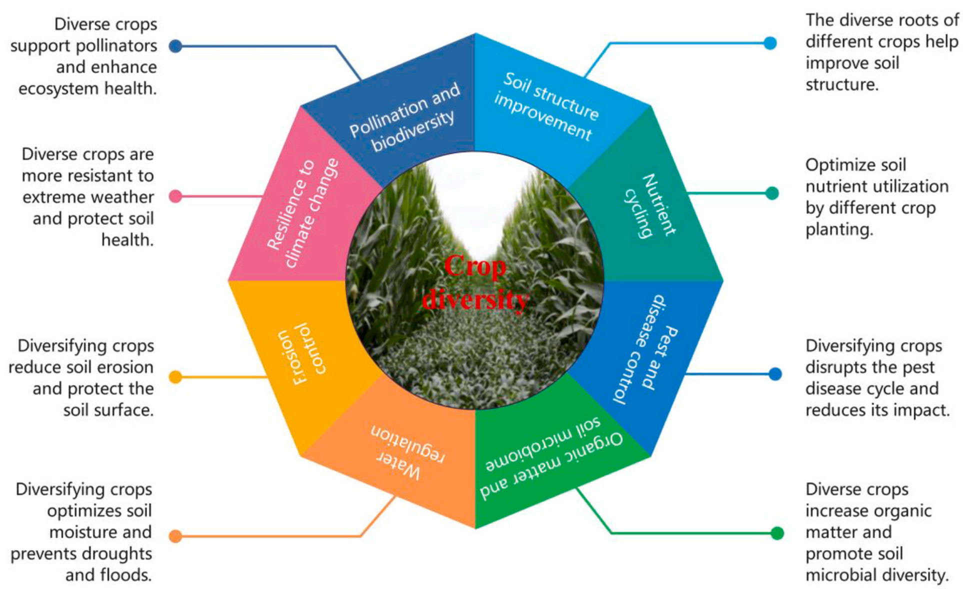

Fig. 2. Ecological service effects of crop diversity on soil health.

that promote crop diversity. Rotating different crops or planting multiple crops at the same time can significantly improve soil quality and productivity (Chahal et al., 2021). Crop rotation helps mitigate the spread and accumulation of soil-borne pests and diseases associated with the continuous cultivation of a single crop (Yu et al., 2022). Furthermore, varying planting methods can alter the microbial composition of the soil, aiding in the suppression of pests and pathogens, thereby reducing reliance on pesticides (Meena et al., 2020). Additionally, crop rotation enhances nutrient use efficiency within the soil. Different planting methods exhibit distinct nutrient demands, which can minimize nutrient wastage and improve nutrient recycling rates. In the context of intercropping, the synergistic interactions among various crops can increase the diversity of soil microorganisms (Stefan et al., 2021). Root exudates from different crops can enhance soil structure, boost organic matter content, and support the proliferation and growth of soil microorganisms (Upadhyay et al., 2022). Moreover, the variations in growth cycles and characteristics among different crops can optimize the utilization of soil resources and improve overall soil quality (Qiao et al., 2022). By strategically designing crop rotation and intercropping systems, it is possible to enhance the microbial composition of the soil, reduce the incidence of soil pests and diseases, and improve nutrient use efficiency, thereby contributing to the sustainable development of agriculture.

3.2. *Crop diversity co-benefit crops and microbes*

Crop diversity often facilitates the restoration of the soil microbial community through alterations in soil biodiversity. The cultivation of crops such as corn, soybeans, and wheat can influence both the diversity and abundance of soil microorganisms. The organic acids released by the root systems of various plant types significantly impacts the structure and function of the soil microbial community. Moreover, the rhizobia exuded by the root systems of leguminous plants establish a symbiotic relationship with the roots, thereby enhancing the nitrogen content in the soil and promoting the nitrogen cycle (Abd-Alla et al., 2023). Additionally, planting diverse crop types can alter the biodiversity of soil parasites and subsequently affect soil health (Yang et al., 2020). Continuous monoculture may lead to the extensive proliferation of certain pathogenic parasites, resulting in an increase in soil pathogens and posing a threat to crop health (Fones et al., 2020). Conversely, cultivating a variety of crops can mitigate the incidence of parasites and enhance soil health.

Soil nutrient cycling refers to the transformation and utilization of various nutrients in different forms within the soil (Fig. 3). Different crops have unique nutritional needs throughout their growth. Some may severely deplete specific nutrients, leading to a reduction in their availability, while others may efficiently utilize alternative nutrients, thereby maintaining a balanced nutrient cycle (Bai et al., 2024b). The diverse root structures and secretions of various crops can enhance the accumulation of organic matter in the soil, thereby improving nutrient cycling and increasing the soil's resilience to shocks and disturbances, such as drought, extreme temperatures, and intensive agricultural practices (Wei et al., 2024). Furthermore, crop diversity can influence the activity of soil microorganisms, which in turn affects the cycling of soil nutrients. The substances secreted by the root systems of various crops can attract different types of microorganisms, some of which promote the mineralization and transformation of nutrients, thereby increasing the nutrient supply in the soil (Das et al., 2022b).

The cultivation of diverse crops within the same area may lead to the emergence of similar diseases, and this monoculture management approach can facilitate the spread of such diseases. Conversely, introducing a variety of crops can enhance microbial diversity in the soil, which, in turn, inhibits the growth and dissemination of pathogens. The distinct root structures and secretions of different crops also promote the growth and reproduction of beneficial microorganisms, thereby improving soil health (Hartmann and Six, 2023). Furthermore, different crops exhibit varying levels of adaptability to pests, and practices such as crop rotation or intercropping can mitigate pest occurrences (Liu et al., 2022a). Some crops contain components that suppress pests, and the cultivation of adjacent crops can foster mutual benefits, creating a natural pest control system.

3.3. *Crop diversity for enhanced soil resilience*

Selecting an appropriate crop planting structure and implementing crop rotation and intercropping can effectively reduce the depletion of specific nutrients in the soil while minimizing the incidence of soil-borne diseases and pests. The judicious application of both chemical and organic fertilizers helps to balance the nutrient content in the soil, ensuring that crops receive the necessary nutrients for optimal growth (Bhunia et al., 2021). In addition to these practices, crop diversity enhances soil resilience through various underlying mechanisms. Diverse cropping systems introduce a range of root architectures and depths, which improve soil structure and texture, increase soil permeability, and

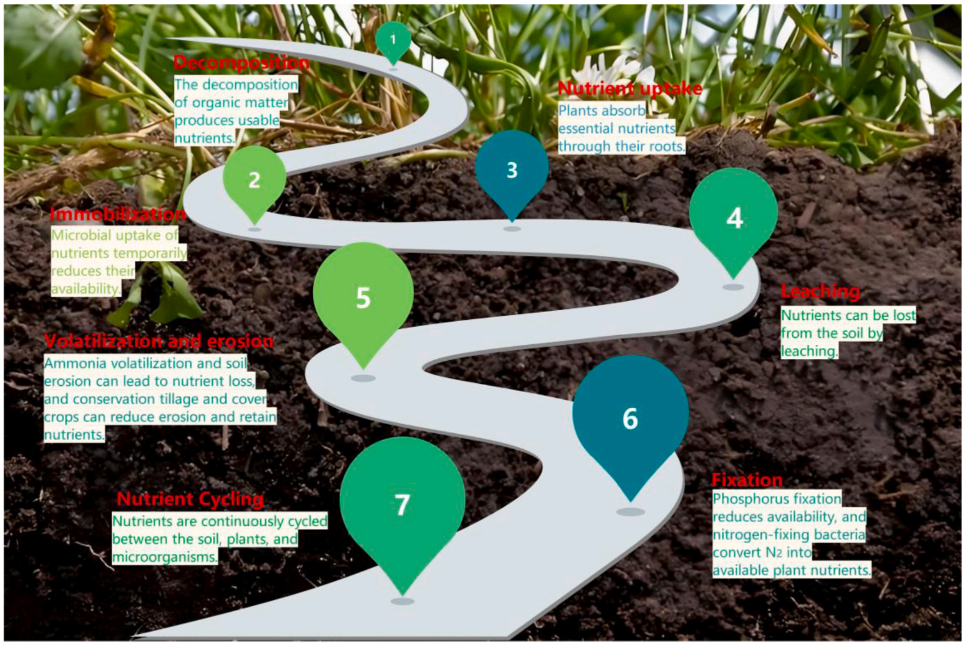

Fig. 3. Soil nutrient cycling is a critical ecological process that involves the transformation, movement, and recycling of nutrients within the soil environment.

enhance water-holding capacity. These structural improvements facilitate better water infiltration and retention, thereby reducing the risk of erosion and improving the soil's ability to withstand extreme weather conditions.

Furthermore, crops with different root exudates support a more diverse and functional soil microbial community (Zhou et al., 2023). This microbial diversity is crucial for nutrient cycling, as various microorganisms specialize in decomposing different organic matter components and mobilizing nutrients for plant uptake. Additionally, a diverse microbial community can suppress soil pathogens through competitive exclusion and the production of antimicrobial compounds, thereby reducing the incidence of soil-borne diseases (Tian et al., 2022). The presence of multiple plant species also disrupts the life cycles of pests and pathogens, making it harder for them to establish and proliferate.

Crop diversity also contributes to the resilience of the soil ecosystem by enhancing nutrient use efficiency. Different crops have varying nutrient requirements and uptake patterns, which prevents the monopolization of specific nutrients and reduces the likelihood of nutrient depletion. This complementary nutrient usage ensures a more balanced and sustainable nutrient profile in the soil. Moreover, diverse root systems create a more heterogeneous soil environment, which supports a wider range of soil organisms, including beneficial bacteria, fungi, and invertebrates. These organisms play vital roles in maintaining soil health by decomposing organic matter, promoting soil aggregation, and improving soil structure.

The synergistic interactions between diverse plant roots and soil microorganisms promote the formation of stable soil aggregates, which enhance soil structure and resilience against physical disturbances. These aggregates improve soil aeration and water infiltration while reducing compaction, thereby creating a more conducive environment for root growth and microbial activity. Specifically, crop root systems enhance soil porosity by creating macropores that facilitate water and air movement, and increase aggregate stability by binding soil particles with root exudates and fungal hyphae, leading to a 15–25 % increase in mean weight diameter of aggregates and a 10–20 % increase in porosity in the root zone (Cárceles Rodríguez et al., 2022). Additionally, diverse plant residues provide a continuous supply of organic material for decomposition, ensuring a steady release of nutrients and maintaining soil organic matter levels.

Variations in root exudates and residue composition among different plant species not only provide additional substrates for soil microorganisms but also create niches for a diverse array of microbial taxa (Zha et al., 2022). This microbial diversity enhances the soil's ability to recover from disturbances, such as drought or pest outbreaks, by ensuring that multiple functional groups are available to respond to changes in environmental conditions. Consequently, crop diversity significantly influences soil health and the resilience of the agricultural ecosystem. By judiciously employing diverse planting methods, it is possible to enhance farmland productivity and ecological stability, thereby achieving sustainable agricultural development. Future agricultural production should place greater emphasis on the role of crop diversity in promoting soil health and ecosystem resilience, while continuously fostering the healthy development of the agricultural ecosystem.

4. Harnessing the crop-soil-microbe synergies for sustainable agriculture

4.1. The rhizosphere microorganisms; an overview

The structure of rhizosphere microbial communities pertains to the composition and organization of microbial populations in soil that are in contact with plant roots (Fig. 4). These microbes include bacteria, fungi, actinomycetes, and archaea, among various other microorganisms. The diversity of rhizosphere microbial communities is closely linked to the biological, biochemical, and ecological characteristics of the soil (Bian et al., 2020). A rich and diverse microbial community can enhance nutrient cycling efficiency, suppress soil-borne diseases, and promote plant growth and development (Niu et al., 2020). Nitrogen-fixing bacteria contribute nitrogen nutrients to plants, while antagonistic fungi bolster plant resistance to soil-borne diseases (Ahmed et al., 2023). Furthermore, soil microorganisms decompose organic matter, releasing carbon dioxide, and can also facilitate carbon sequestration in the soil, thereby aiding in the mitigation of greenhouse gas emissions (Raza et al., 2023). By regulating the structure of rhizosphere microbial communities, soil quality can be improved, farmland ecosystems can be preserved, and sustainable agricultural development can be achieved.

Nitrogen-fixing bacteria are microorganisms present in the soil that convert nitrogen gas and nitrogen compounds, which are not usable by

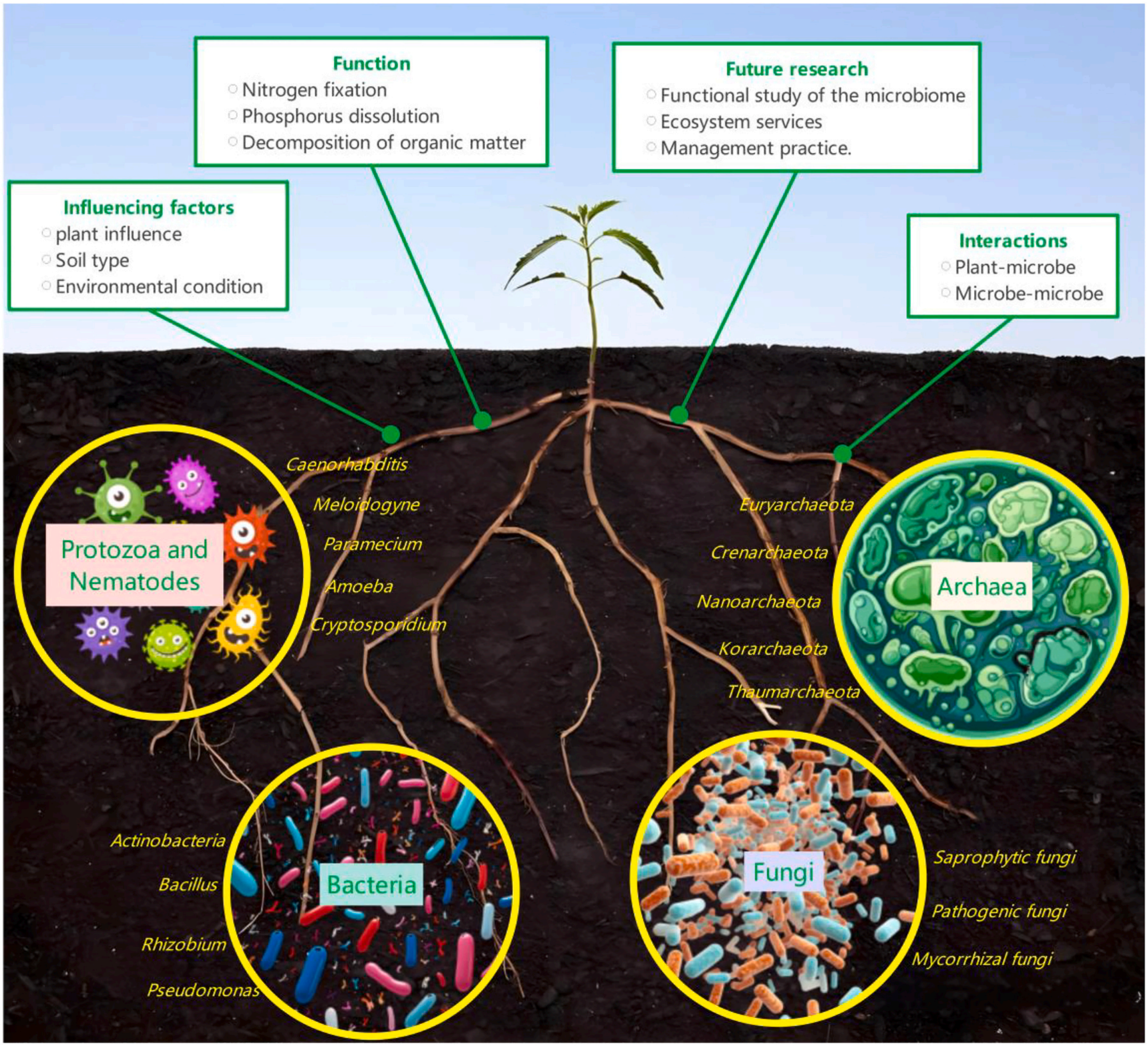

Fig. 4. Rhizosphere microbial community structure plays a crucial role in plant growth and soil health.

plants, into forms that can be absorbed by plants, thereby enriching the nitrogen resources of the soil (Harindintwali et al., 2020). Nitrifying bacteria oxidize ammonia nitrogen into nitrate nitrogen, which serves as a crucial nitrogen source for plants. Denitrifying bacteria reduce nitrate nitrogen to nitrogen gas in anoxic environments, releasing it into the atmosphere and regulating soil nitrogen content to maintain a nitrogen balance (Li and Zhou, 2020). Additionally, rhizosphere nitrogen-fixing bacteria can form symbiotic nodules with plants, converting nitrogen gas into nitrogen compounds that are absorbable by plants, thus providing essential nutrients for plant growth (Fahde et al., 2023). Furthermore, rhizosphere microorganisms can produce auxins, which promote plant growth and development.

Microorganisms play a crucial role in the decomposition of organic matter by releasing organic acids and enzymes that degrade complex organic nutrients, thereby making them more accessible to crops (Table 2). Additionally, these microorganisms synthesize growth hormones such as gibberellins and jasmonic acid, which promote root growth and expand the nutrient absorption area (de Andrade et al., 2023). They enhance the uptake of phosphorus, nitrogen, and other essential elements from the soil through symbiotic interactions with mycorrhizal fungi, effectively improving nutrient utilization efficiency (Mitra et al., 2023). At the molecular level, nitrogen-fixing bacteria

Table 2
Microorganisms release organic acids and enzymes that promote the breakdown of organic matter, thereby improving the utilization of crop nutrients.

Microorganism type	Released organic acids	Released enzymes	Degraded organic matter	Effect on nutrient availability	Ref.
Bacteria	Acetic acid, Citric acid	Cellulases, Proteases	Cellulose, Proteins	Increases N, P, K availability	(Xian et al., 2022)
Fungi	Oxalic acid, Gluconic acid	Ligninases, Amylases	Lignin, Starch	Enhances soil structure and nutrient cycling	(Corbu et al., 2023)
Actinomycetes	Lactic acid, Propionic acid	Chitinases, Phosphatases	Chitin, Organic phosphates	Solubilizes phosphate, improves micronutrient availability	(Kaur et al., 2024)
Archaea	Sulfuric acid	Ammonia Oxidases	Ammonia	Nitrification, enhances nitrogen availability	(Luo et al., 2024)
Protozoa	Acetic acid, Butyric acid	Various Hydrolytic Enzymes	Various organic debris	Releases nutrients by consuming bacteria and fungi	(Bhujbal et al., 2022)
Yeasts	Malic Acid, Succinic acid	Invertases, Lipases	Sugars, Lipids	Increases carbon availability	(Gong et al., 2024)

convert atmospheric nitrogen into ammonia through the enzymatic action of nitrogenase, a process critical for incorporating nitrogen into organic compounds that plants can utilize (Xing et al., 2025). Phosphorus-solubilizing bacteria release organic acids and protons that solubilize insoluble phosphate compounds, making phosphorus available for plant uptake (Zhang et al., 2025).

Furthermore, rhizosphere microorganisms can convert soil nitrogen into inorganic forms that are absorbable by resilient roots, thereby enhancing nitrogen utilization efficiency. Microorganisms are also capable of decomposing insoluble phosphates, converting them into forms that plants can readily absorb. On a microstructural level, microbial activity contributes to the formation and stabilization of soil aggregates by producing extracellular polymeric substances and facilitating the binding of soil particles. These aggregates improve soil structure by increasing pore space, enhancing aeration, and boosting water retention capacity, which are critical factors for root penetration and nutrient transport (Philippot et al., 2024).

Rhizosphere microorganisms play an indispensable role in soil health by promoting nutrient absorption in crops through various mechanisms and enhancing the chemical and physical properties of the soil. By implementing scientifically informed fertilization practices and effective crop rotation strategies, we can promote the diversity and richness of soil microorganisms, thereby contributing to the achievement of sustainable agricultural development goals.

4.2. Effects of microorganisms on crop growth

Microbial activity in the soil fosters the formation of soil aggregates, which improves soil structure, increases aeration and water retention, and ultimately benefits crop growth. Biofertilizers comprise a diverse array of beneficial microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing fungi, and potassium-solubilizing bacteria. These microorganisms interact symbiotically or synergistically with plant root systems through intricate molecular signaling pathways that enhance nutrient absorption and utilization by plants ((Harman et al., 2021). For instance, the exchange of flavonoids and Nod factors between legumes and rhizobia bacteria initiates root nodulation and nitrogen fixation (Wang et al., 2019).

Additionally, biofertilizers play a crucial role in decomposing organic matter in the soil, which releases essential nutrients for plant uptake. Through enzymatic breakdown, organic matter is transformed into simpler molecules such as nitrates, ammonium, and soluble phosphates that are readily available to plants, ensuring adequate nutrition for crops. Furthermore, the presence of microorganisms in this ecosystem not only improves soil fertility but also enhances plant resistance, thereby reducing the incidence of pests and diseases (Elnahal et al., 2022).

Microbial-induced disease resistance is increasingly employed in agricultural production to reduce reliance on chemical pesticides and mitigate environmental pollution (Fig. 5). The microorganisms found in plant growth promoters can stimulate the root system to secrete specific compounds that inhibit pathogen growth (Ravelo-Ortega et al., 2023). Additionally, these microorganisms can produce antibiotics that directly kill pathogens, thereby playing a crucial role in disease suppression. They also activate the plant defense system by upregulating the expression of pathogenesis-related proteins and enhancing the production of reactive oxygen species, which are involved in signaling pathways that fortify plant defenses (Koza et al., 2022). Furthermore, microorganisms can regulate the endogenous hormone levels in plants, such as increasing salicylic acid and ethylene, which improves stress resistance and strengthens their defense against pathogens.

Microorganisms can alleviate biological stresses in crops through multiple pathways. They produce antibiotics and volatile organic compounds that effectively combat the invasion of pathogens or parasites, thereby reducing the severity of crop diseases. Certain soil bacteria generate antifungal substances that inhibit fungal growth, thus

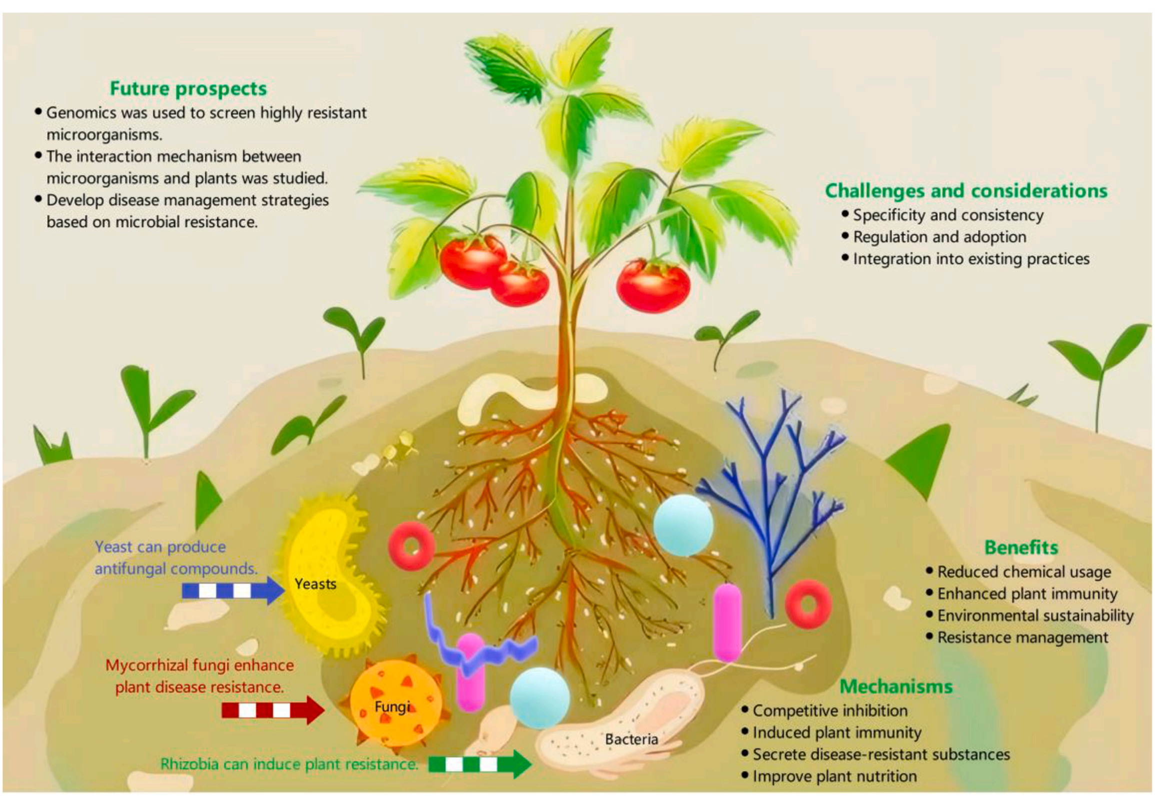

Fig. 5. Microbial induced disease resistance uses specific microorganisms to enhance plant defenses and improve plant resistance to pathogens by activating defense mechanisms.

protecting crops from fungal infections. Furthermore, microorganisms can promote the development and enhancement of the crop immune system, increasing resistance to pathogens (Tiwari et al., 2022). Through symbiosis with the plant rhizosphere, microorganisms can activate the plant defense system, thereby enhancing immunity to diseases (Nishad et al., 2020). Additionally, microorganisms can induce the production of anti-disease proteins in plants, further augmenting disease resistance (Wu et al., 2021). By promoting rhizosphere activity, microorganisms enhance the plant's nutrient absorption capacity, improve growth rates, and ultimately bolster the crop's resilience to biological stresses.

4.3. Effects of crops on soil microbial diversity

Different crop planting methods can significantly alter the structure and richness of the soil microbial community. The traditional monoculture cropping pattern often leads to the excessive proliferation of certain microbial species while inhibiting the growth of others, ultimately reducing the overall diversity of soil microbes (Kunguang et al., 2024). In contrast, plant root exudates can promote the growth of beneficial microbes in the soil, thereby increasing microbial diversity (Agarwal et al., 2023). Furthermore, specific crop planting patterns may lead to a decline in certain functional microbes, which can diminish the ecosystem functions of the soil. Conversely, diversified planting patterns can enhance the diversity of soil microbes and contribute to the stability and health of the soil ecosystem.

Different crop plantings can lead to alterations in the diversity and structure of the soil microbial community, thereby influencing the stability and function of the soil ecosystem (Hartmann and Six, 2023). Notably, significant variations exist in how different crops affect soil microbes. For instance, crops such as corn, wheat, and soybeans exert a more substantial impact on soil microbial diversity, whereas crops like rice and cotton have a relatively lesser influence. The differences in growth cycles, along with the types and quantities of root exudates produced by various crops, significantly affect the growth, reproduction, and metabolic activities of soil microbes (Iannucci et al., 2021). Additionally, the high nutrient requirements of crops can intensify competition for specific nutrients in the soil, consequently affecting the structure and function of the soil microbial community. The root exudates and rhizosphere substances released by crop roots play a crucial role in influencing the growth and metabolism of soil microbes, thereby impacting soil microbial diversity. Furthermore, the distinct root morphology and structure of different crops can lead to changes in the distribution and abundance of microbes within the soil, ultimately affecting the diversity of the soil microbial community (Zhou et al., 2022).

The excessive application of fertilizers can lead to the overgrowth of specific microbial populations in the soil, adversely affecting the survival and reproduction of other microbial communities, ultimately resulting in a reduction of microbial diversity (Šimanský et al., 2024). Traditional tillage practices may compromise soil structure and diminish both the quantity and variety of soil microbes (Gupta et al., 2022). In contrast, no-till or reduced-tillage practices can help to preserve soil microbial diversity. Furthermore, the implementation of cover crops and crop rotation can enhance soil microbial diversity while maintaining the balance of soil nutrients.

5. Soil management and sustainable agriculture

5.1. Maintenance and increase of soil fertility

The fertility level of soil directly influences crop growth and yield. To maintain soil fertility, it is essential to understand the nutrient content of the soil and to apply fertilizers based on the specific nutrient requirements of different crops. Nitrogen, phosphorus, and potassium are critical nutrients for crop development, and deficiencies in any of these elements can adversely affect crop growth. Consequently, regular soil nutrient testing and targeted fertilization based on test results are vital for sustaining soil fertility. Additionally, the use of organic fertilizers represents an important strategy for maintaining soil health. Organic fertilizers are rich in organic matter and microorganisms, which can enhance microbial activity, improve soil structure, and increase overall soil fertility (Han et al., 2021). By applying the appropriate amount of organic fertilizers, the organic matter content in the soil can be elevated, thereby improving the soil's capacity to retain moisture and nutrients while providing balanced nutrition to crops. Different soil types and crops necessitate distinct fertilization methods. Common techniques include basal fertilization, top-dressing, fertigation, and foliar spraying. Implementing scientific fertilization practices can maximize fertilizer efficiency, reduce nutrient loss, and minimize soil pollution (Barłóg et al., 2022).

Terracing can effectively slow rainwater runoff, thereby reducing soil erosion and sediment accumulation (Meng et al., 2024). The design of terraces and the construction of drainage systems are critical factors in minimizing both soil and water loss. Additionally, vegetative cover on the soil surface can effectively suppress wind and water erosion, further mitigating soil loss. This is particularly important in arid and mountainous regions, where vegetation cover plays a crucial role in soil protection. Furthermore, rational soil and water conservation projects serve as effective measures for erosion control. Techniques such as constructing ditches, greening deserts, and restoring ecosystems can significantly reduce soil and water loss, thereby protecting land resources (Li et al., 2021).

Proper irrigation can enhance both crop yield and quality by promoting the efficient utilization of soil nutrients (Zhang et al., 2023). Conversely, over-irrigation may lead to salt accumulation in the soil, negatively impacting crop growth. Additionally, inadequate drainage can result in insufficient oxygen supply to plant roots, thereby impairing normal plant development. Implementing scientifically sound and rational irrigation and drainage management practices can improve crop yield, protect the soil environment, and contribute to sustainable agricultural development. Consequently, farmers and agricultural managers should prioritize effective irrigation and drainage management while continually seeking optimal management models tailored to local conditions.

5.2. Sustainable agriculture

Conservation tillage minimizes soil exposure to external environments by utilizing cover crops to protect the soil surface. This practice reduces the risk of soil erosion (Bai et al., 2024a), decreases both water and soil loss, and enhances soil structure and quality, ultimately leading to increased agricultural yield and productivity (Zhang et al., 2021b). By decreasing the frequency of plowing, carefully controlling irrigation amounts, and judiciously applying fertilizers, soil compaction and erosion can be minimized, beneficial microbial activity can be promoted, and soil fertility and health can be improved (Rehman et al., 2022). Furthermore, conservation tillage enhances soil permeability and water retention, facilitates gas exchange within the soil, and supports root growth and nutrient uptake (Li et al., 2020).

In organic agriculture, farmers avoid the use of synthetic fertilizers and chemical pesticides. Instead, they enhance soil fertility and maintain ecological balance through the application of organic fertilizers and biological pesticides. Organic farming promotes soil biodiversity and microbial activity, which improve soil structure and water retention, ultimately enhancing both crop yield and quality. This approach advocates for the recycling of agricultural waste and biomass, ensuring the healthy growth of both soil and plants while maximizing resource utilization. The practice of organic agriculture not only improves soil quality but also contributes to the protection of groundwater resources and the maintenance of ecosystem balance (Gamage et al., 2023). By minimizing the use of chemical pesticides and fertilizers, organic farming reduces soil and water pollution, thereby mitigating negative environmental impacts. Organic agriculture represents a sustainable farming practice that utilizes natural resources while safeguarding the ecological environment. Through these practices, soil fertility and productivity can be enhanced, farmland ecological environments can be protected, and sustainable agricultural development can be promoted. The promotion and implementation of organic agriculture hold significant promise for achieving sustainable agricultural development and conserving environmental resources.

The utilization of GPS, satellite remote sensing, and sensor technology facilitates precise monitoring and management of soil and crop growth. Based on these monitoring results, farmers can adjust fertilization, irrigation, and pest control measures, thus achieving efficient and sustainable agricultural production. Gene editing technology also significantly contributes to sustainable agriculture by enabling the development of crop varieties that are resistant to pests and diseases and adaptable to climate change (Table S1). This innovation enhances crop yield and resilience while reducing dependency on chemical pesticides and fertilizers, which, in turn, lowers soil pollution. Furthermore, gene editing can improve soil microorganisms, promoting the growth and function of beneficial microbes and enhancing both soil health and crop quality (Ortiz and Sansinenea, 2022). Drones can execute precise pesticide applications, irrigation, and crop protection operations, thereby reducing labor input and the use of chemical pesticides, which consequently lowers production costs and minimizes negative impacts on soil and the environment (Fig. 6). Additionally, drones can rapidly gather farmland data, enabling farmers to promptly address challenges such as pests and climate change. The integration of precision agriculture technology, gene editing technology, and drone technology can significantly enhance agricultural production efficiency, reduce environmental damage to soil, increase crop yields, and improve soil health. Therefore, it is essential to actively promote the application of modern technology in agricultural production to foster sustainable agricultural development.

5.3. Soil management policies and frameworks

International soil management policies encompass several key aspects, including soil protection, land use planning, soil improvement, and pollution control (Fig. 7). Firstly, governments enhance soil protection through legislative and policy measures that limit excessive land exploitation and usage, thereby preventing land degradation and desertification. Secondly, land use planning serves as a crucial tool for maintaining soil quality and ecological balance. Through scientific planning and the rational use of land resources, these policies aim to protect the environment and sustain ecological equilibrium. Furthermore, soil improvement and pollution control are significant components of international soil management policies. Governments allocate funds and deploy technology to restore and manage polluted soils, thereby enhancing soil quality and productivity.

The funding sources for sustainable agriculture projects primarily include government grants, funding from international organizations, and donations from agricultural enterprises (DeLonge et al., 2016). Government grants typically support research and development in agricultural technology, as well as the construction of agricultural production facilities aimed at enhancing production levels and efficiency. International organizations play a crucial role in sustainable agriculture projects by providing financial support, technical assistance, and training services, thereby promoting sustainable agricultural development in developing countries and regions. Donations from agricultural enterprises can assist producers in adopting more environmentally friendly farming practices and improving crop quality, thus contributing to the achievement of sustainable agricultural development goals. Indirect subsidies involve funding for agricultural research institutions, educational training institutions, and agricultural technology service

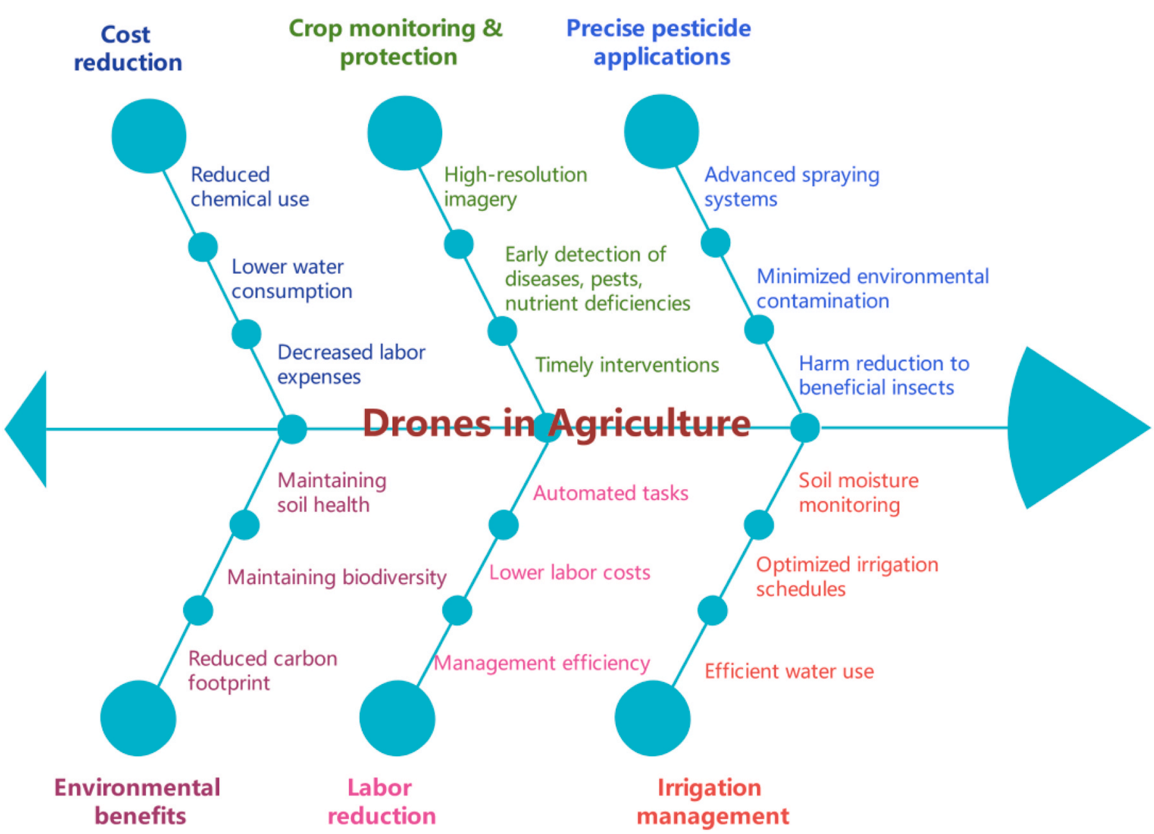

Fig. 6. Drones enhance agricultural efficiency by precisely applying pesticides, irrigation, and crop protection, reducing labor, chemical use, production costs, and environmental impact.

Fig. 7. International cooperation and knowledge sharing are crucial for effective soil management to address global soil degradation and pollution, which significantly impact food security, biodiversity, and climate change.

centers, which provide technical guidance and training services, promote advancements in agricultural technology, and ultimately increase production efficiency and quality.

Socio-economic factors in soil management significantly influence soil quality and productivity. Soil degradation not only diminishes farmland yield and quality but also adversely affects the ecosystem (Wang, 2022). Overuse and mismanagement of land have exacerbated soil erosion, seriously affecting agricultural production and ecological sustainability (Borrelli et al., 2017). Therefore, it is essential to formulate effective soil management policies and measures aimed at enhancing soil quality and productivity to achieve sustainable agricultural development.

6. Conclusions and future prospects

This review primarily explores the intricate relationships among crops and soil characteristics, crop diversity, rhizosphere processes and soil health, crop-soil microbial interactions, and soil management within the context of sustainable agriculture. Our findings indicate that crop cultivation exerts a profound influence on the physical, chemical, and biological properties of soil. The distinct root structures, growth patterns, and nutrient requirements of various crops lead to significant variations in nutrient distribution and cycling within the soil, which subsequently affects soil fertility and water retention capabilities. Key factors such as soil pH, organic matter content, and microbial community structure play pivotal roles in influencing nutrient uptake and stress resistance in crops. Furthermore, the relationship between crop diversity and soil health is particularly striking. Practices such as crop rotation and intercropping not only promote microbial diversity in the soil, but also enhance its disease suppressiveness ability, mitigating the risk of soil degradation through the overuse of specific nutrients

The symbiotic interactions between crops and soil microbes is crucial for maintaining the delicate balance of soil ecosystems. Organic substances released by crop roots provide energy and nutrients for soil microbes, promoting their growth and metabolic activity. In return, these microbes facilitate crop growth through vital processes such as nitrogen fixation and phosphorus solubilization, underscoring the importance of healthy crop-soil interactions.

As climate change intensifies and the global population continues to grow, the demand for soil nutrients will inevitably increase. Consequently, it is imperative to investigate the adaptability of various crop varieties to different soil types and to explore methods for enhancing crop yields through enhancing soil fertility. The synergies between crops and soil microorganisms represents a valuable area of research, as these microorganisms play a crucial role in the soil ecosystem and can influence multiple aspects of crop growth and disease resistance.

Future studies could examine the effects of diverse agricultural practices on soil microbial community structures and identify effective strategies for harnessing beneficial microorganisms to promote crop growth. Additionally, adopting diverse cropping systems can enhance soil structure, sustain soil fertility, and mitigate the prevalence of pests and diseases. Thus, future research should investigate the impact of various crop cover practices on soil protection and assess how diverse planting strategies can contribute to sustainable agricultural development. Future research should focus on integrating precision agriculture technologies to monitor soil health in real time and investigating the roles of specific microbial communities in enhancing crop resilience. Additionally, exploring climate-resilient cropping systems and soil organic carbon sequestration practices can mitigate environmental impacts. Engaging farmers in participatory research and advocating for supportive policies will also be crucial for promoting sustainable agricultural practices that balance productivity with ecological health. Overall, the future of agricultural sustainability hinges on understanding the complex interrelationships between crops and soil.

CRediT authorship contribution statement

Yingying Xing: Writing – original draft, Investigation, Data curation, Conceptualization. **Adnan Mustafa:** Writing – review & editing. **Xiukang Wang:** Writing – review & editing, Resources, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2025.117703.

Data availability

Data will be made available on request.

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