

Meta Analysis

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Root-Soil Interactions Affecting Maize Growth

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Abstract The relationship between the roots of corn and the soil is of great significance to the growth, nutrient absorption and stress resistance of the crop. Many studies have shown that the morphology of roots, their secretions, and their interactions with the soil environment and microorganisms can affect corn's utilization efficiency of key resources such as water, nitrogen, and phosphorus, as well as its yield. Root secretions not only improve the environment around the roots but also attract beneficial microorganisms, assist in nutrient cycling, and make the soil healthier. Some agricultural practices, such as precise fertilization, adding soil conditioners, and cultivating varieties with better root systems, can also enhance the "root-soil interaction" effect, thereby improving the stress resistance and resource utilization rate of corn. In the future, if high-throughput phenotypic technology of root systems, soil science, microbiomics and agronomy are combined, it will be able to provide more assistance in cultivating high-yield, stress-resistant and sustainable corn varieties and planting methods. A thorough understanding and application of root-soil interaction are of vital importance for food security and sustainable agricultural development. The purpose of this study is to summarize and analyze these aspects to provide references for subsequent corn improvement and agricultural management.

Keywords Corn; Root-soil interaction; Root phenotype; Soil microorganisms; Sustainable agriculture

1 Introduction

Corn (*Zea mays* L.) is one of the most important food crops in the world. It is not only the main food source for humans and animals, but also the main raw material for industry and bioenergy. The yield and quality of corn directly affect global food security and sustainable agricultural development. In recent years, with the increase in population and the intensifying pressure of climate change, how to enhance the production efficiency and resource utilization rate of corn has become an important issue in agricultural research.

The root system is an important organ for the exchange of matter and energy between crops and soil. The interaction between roots and soil can affect the absorption of water and nutrients, as well as the microbial community in the rhizosphere, soil structure and physical and chemical properties, etc. These factors, in turn, can have an impact on the growth, development and yield of corn. Root secretions can regulate microbial composition, promote the colonization of beneficial bacterial communities, assist nutrient transformation and enhance stress resistance (Yu et al., 2021; Shi et al., 2024; Luo et al., 2025). The physical structure of soil (such as porosity and compaction), chemical properties (such as pH and nutrient content), and biological activities (such as microbial diversity) jointly affect the rhizosphere environment, directly influencing the growth space and functional performance of crop roots (Lu et al., 2020; Zhang et al., 2023; Nassir et al., 2024; Peng et al., 2024; Gao et al., 2025).

This study summarizes the latest research progress on the root-soil interaction of maize crops in recent years, mainly focusing on three aspects: physical interaction, chemical interaction and biological interaction. Physical interaction mainly analyzes the influence of soil structure, compactness and water distribution on root growth and function. Chemical interaction explores the relationship among soil nutrient dynamics, pH changes, root secretions and nutrient availability. Biological interaction studies the structure and function of rhizosphere microbial communities, as well as their relationship with root development, nutrient absorption, and stress resistance. By integrating field experiments, greenhouse studies and multi-omics data, this research aims to reveal the mechanism by which root-soil interactions affect the growth and yield of corn, providing theoretical and practical support for efficient and sustainable corn production.

2 Root System Architecture of Maize

2.1 General features of maize root morphology (primary, seminal, nodal, and lateral roots)

The root system of corn is composed of various types of roots, including primary roots, embryonic roots (also known as secondary roots), node roots (crown roots and supporting roots), and lateral roots. The primary roots and embryonic roots belong to the embryonic root system. They are formed after the seeds germinate and provide support for the early water and nutrient absorption of the seedlings. The node root develops from the base of the stem during the growth of the plant and is the main source of the biomass of the root system of mature plants. Lateral roots grow out from the primary roots, embryonic roots and node roots, greatly increasing the surface area of the roots and facilitating more efficient absorption of water and nutrients. Different types of roots have obvious differences in structure and function. Together, they constitute the complex Root System Architecture (RSA), providing a basis for corn to adapt to the variable soil environment (Hochholdinger et al., 2018; Rivas et al., 2022; Guo et al., 2025).

2.2 Plasticity of root growth under variable soil conditions

The root system of corn has strong plasticity and can adjust its growth pattern according to conditions such as soil moisture, nutrients and density. In the case of high-density planting or water shortage, corn will reduce the number and length of jointed roots and lateral roots, but maintain the extension of the main root to expand the soil exploration range and reduce rhizosphere competition. In areas with more nitrogen or phosphorus in the soil, roots will increase branching, and different types of roots (such as primary roots, embryonic roots, crown roots, and supporting roots) respond differently to nutrient distribution. This indicates that the root system can adapt to the spatial differences of soil resources. In addition, different genotypes have differences in the hydraulic structure and anatomical characteristics of roots, which will affect their ability to absorb water and resist drought (Rishmawi et al., 2023; Protto et al., 2024).

2.3 Root exudation and its role in modifying the soil environment

Corn roots secrete organic acids, enzymes and secondary metabolites, etc. These secretions can significantly alter the physical, chemical and biological properties of the rhizosphere soil. They can regulate soil pH, promote the release of insoluble nutrients (such as phosphorus), and also influence the composition of microbial communities, enhance the activity of beneficial microorganisms, and help with nutrient cycling and stress resistance. Under adverse conditions such as drought or nutrient deficiency, the composition and release amount of secretions will change, thereby regulating the enzyme activity and microbial diversity in the rhizosphere and improving the adaptability of corn (Hu et al., 2018; Hao et al., 2022; Adeniji et al., 2024). In addition, root hairs and secretions can also work in synergy to expand the influence range of the rhizosphere, enhance soil enzyme activity, and accelerate the decomposition of organic matter (Bilyera et al., 2021; Zhang et al., 2022).

3 Soil Physical Properties and Root Interactions

3.1 Influence of soil texture, structure, and compaction on root penetration

The texture and structure of the soil can affect the resistance encountered by the root system and the distribution of rhizosphere volume density. Phalempin et al. (2021) conducted a series of comparative studies. In homogeneous soil, corn roots need to rely on their own growth to push soil particles and gradually form pores. In soils with significant structural differences, the roots of corn tend to grow along the existing pores, reducing soil compaction. If the compaction of the soil increases (such as compaction caused by mechanical tillage or tire rolling), the bulk density and penetration resistance of the soil will also increase, which will limit the downward and outward expansion of corn roots, resulting in reduced root length, root surface area and root dry weight, and ultimately affecting the absorption of water and nutrients (Rut et al., 2021; Nawaz et al., 2023; Nassir et al., 2024; Zhu et al., 2024; Gao et al., 2025). When the penetration resistance exceeds 2 200 kPa, the growth of corn roots almost stops. Although the diameter of the fine roots of corn will increase in this case to enhance the penetration power, the overall distribution of the root system will still be limited.

3.2 Role of soil moisture availability and aeration in root growth

Soil moisture and aeration can jointly affect root growth. Appropriate amounts of water can reduce mechanical resistance and promote root extension and branching (Jaswal and Sandal, 2024). Drought or excessive dryness

will significantly increase resistance, reducing root length and root volume. When the soil is already very tight, the inhibitory effect of drought is more obvious (Zhu et al., 2024). If the soil has poor aeration, such as excessive density or supersaturation of water, it will inhibit root respiration and microbial activity, and reduce root vitality and nutrient absorption efficiency (Yu et al., 2024). There are many ways to improve soil aeration, such as increasing organic matter or using aerated irrigation. These methods can significantly increase root length, root surface area and dry weight, thereby enhancing yield.

3.3 Interaction with tillage and soil management practices

Farming methods and management measures can alter the physical properties of the soil, and thus also affect the distribution of corn roots. Tillage methods such as deep loosening and rotary tillage can reduce the bulk density and resistance of the soil, increase porosity and moisture content, make it easier for roots to extend deep and laterally, and improve root length density and yield (Jiang et al., 2025). Conservation tillage (no-till, cover crops, etc.) helps maintain soil structure and moisture, but sometimes compacts the topsoil to inhibit root penetration (Nassir et al., 2024). Adopting reasonable methods in the process of corn planting can optimize root distribution, improve the utilization efficiency of water and nitrogen, and increase corn yield (Jaswal and Sandal, 2024).

4 Soil Chemical Properties and Nutrient Dynamics

4.1 Nutrient availability (N, P, K, and micronutrients) and root uptake strategies

Corn has a high demand for nitrogen (N), phosphorus (P), potassium (K), and trace elements. The amount of these nutrients in the soil will directly affect the growth of plants. The combined use of organic fertilizer, phosphorus-dissolved bacteria and mineral fertilizer can significantly increase the contents of N, P and K in soil and plants, thereby promoting absorption and increasing yield (Nigussie et al., 2021; Khan et al., 2025). The root system will adopt some strategies, such as increasing branches in areas with abundant nutrients, prolonging root length or adjusting root shape. Especially in the early stage of growth, the absorption of nitrogen and phosphorus is prominent (Zhang et al., 2023). Measures such as conservation tillage and organic mulching can also improve the chemical properties of the soil, increase organic carbon, total nitrogen and available phosphorus, thereby enhancing the absorption capacity of the root system (Mhlanga et al., 2022; Teresa et al., 2024).

4.2 Root exudates altering soil pH, chelation, and nutrient mobilization

The roots of corn secrete organic acids, enzymes and various metabolites. These substances can alter the pH of the rhizosphere and also promote the release and utilization of insoluble nutrients such as phosphorus, iron and zinc. Organic acids can lower the pH of the rhizosphere, making phosphorus more easily absorbed. They can also chelate metal ions and improve the availability of trace elements (Canellas et al., 2019; Custos et al., 2020; Wang et al., 2022). Root secretions can also help attract some beneficial microorganisms, such as actinomycetes or phosphorus-solubilizing bacteria, which, together with the roots, promote nutrient cycling and enhance stress resistance (Vive-peris et al., 2019; Sun et al., 2021; Zhang et al., 2023). In addition, when corn absorbs different forms of nitrogen, it will also change the pH of the rhizosphere. When absorbing nitrate nitrogen, the rhizosphere becomes more alkaline; when absorbing ammonium nitrogen, the rhizosphere becomes more acidic. Both of these can affect the availability of nutrients (Naeem et al., 2023).

4.3 Impact of soil salinity, acidity, and nutrient imbalances

Soil with high salt or acid content can severely inhibit the growth of corn roots and nutrient absorption. At this time, the roots will secrete organic acids and some stress metabolites to relieve stress. However, in extreme cases, root length, root weight and absorption capacity will still decrease (Naeem et al., 2023). If the soil pH is too low or too high, the absorption of nitrogen, phosphorus, potassium and trace elements will all be affected. Studies have shown that the suitable pH range is between 6.3 and 7.4, which is most conducive to corn growth and nutrient utilization (Sirisuntornlak et al., 2020). By applying lime, ammonium nitrogen fertilizer or organic matter, the soil pH can be regulated and the availability of trace elements (such as Mn, Zn) can be improved, thereby increasing the yield. If the proportion of nutrients is unreasonable, such as an imbalance between nitrogen and phosphorus, it will reduce utilization efficiency and increase environmental risks. The combined use of organic fertilizer and mineral fertilizer can optimize nutrient supply and reduce imbalance problems (Nigussie et al., 2021; Zhang et al., 2023; Teresa et al., 2024).

5 Biological Interactions in the Rhizosphere

5.1 Symbiotic associations (mycorrhizae, rhizobacteria) enhancing nutrient acquisition

Arbuscular mycorrhizal fungi (AMF) and rhizosphere growth-promoting bacteria (PGPR) are the most important symbiotic microorganisms in the rhizosphere of corn. After symbiosis with roots, AMF can significantly enhance the absorption of insoluble nutrients such as phosphorus and potassium. It can also cooperate with rhizosphere bacteria to further improve the utilization efficiency of insoluble nutrients (Lu et al., 2023). PGPR, such as *Bacillus subtilis*, can promote root growth and enhance the utilization of water and nutrients. If combined with AMF, it can also enhance drought resistance and yield (Khan et al., 2024). Combined inoculation of multiple microorganisms (such as AMF, *Azospirillum*, *Pseudomonas*, *Trichoderma*) can not only help better colonization of root systems, but also increase the diversity of rhizosphere microorganisms and enzyme activities, and improve soil ecological functions (Xu et al., 2024).

5.2 Root–microbe signaling and soil enzyme activities

Corn roots communicate signals with microorganisms through secretions (such as organic acids, flavonoids, etc.), which affects the structure and function of the microbial community. These secretions can attract specific beneficial bacterial communities, such as Oxalobacteraceae, thereby helping to enhance nitrogen absorption and plant growth (Yu et al., 2021). Rhizosphere microorganisms produce a variety of hydrolases (such as β -glucosidase, acid phosphatase, chitinase, etc.), which can accelerate the decomposition of organic matter and the nutrient cycle. The activities of these enzymes are simultaneously regulated by root secretions and microbial community composition (Bilyera et al., 2021; Hao et al., 2022; Yim et al., 2022). If AMF and rhizosphere bacteria act synergistically, they can significantly increase soil enzyme activity and carbon mineralization rate, and optimize rhizosphere nutrient dynamics (Zhou et al., 2022).

5.3 Pathogenic interactions (soil-borne diseases and root defense mechanisms)

The rhizosphere microbial community not only promotes nutrient absorption but also acts as a "biological barrier" to prevent the invasion of soil-borne pathogenic bacteria. Corn roots secrete some metabolites (such as benzoxazoline, flavonoids, etc.) to recruit beneficial microorganisms, induce systemic resistance, and thereby enhance the defense ability against pathogenic bacteria (Li et al., 2021). The colonization of AMF on roots can enhance the inhibition of pathogenic fungi (such as *Fusarium*, *Aspergillus*, etc.) by the root system, and also increase the activity of rhizoidal enzymes and reduce the occurrence of diseases (Afridi et al., 2022; Ma et al., 2022). The diversity and functionality of the rhizosphere microbial community are important foundations for the health and stress resistance of corn. More sustainable disease management can be achieved by rationally regulating the microbiome (Li et al., 2021; Chepersogon and Moleleki, 2023) (Figure 1).

6 Environmental Stress and Root–Soil Responses

6.1 Drought stress and adaptive root traits

Drought is the main abiotic factor that limits corn yield, and it makes the root system show strong plasticity. Under water-deficient conditions, corn can enhance its absorption capacity for deep water by deepening the main root, increasing the distribution of lateral roots, and improving the biomass and surface area of the root system (Guo et al., 2020; Hazman and Kabil, 2021). Meanwhile, the root system increases lignin synthesis, activates hormone signals (such as abscisic acid, brassinolide) and antioxidant defense systems, all of which contribute to improving drought resistance (Jiao et al., 2022; Li et al., 2023; Wang et al., 2025). The presence of root hairs and the increase of secretions can also improve the microbial diversity and enzyme activity in the rhizosphere, thereby helping to retain water and promote nutrient cycling (Gholizadeh et al., 2024; Swift et al., 2024; Yuan et al., 2024; Hartwig et al., 2025). In addition, the combined inoculation of arbuscular mycorrhizal fungi and pro-growth bacteria can significantly improve the hydraulic conductivity, photosynthetic efficiency and hormone regulation of roots, and enhance the tolerance of corn to drought and high temperature (Romero-Munar et al., 2023; Lopes et al., 2025).

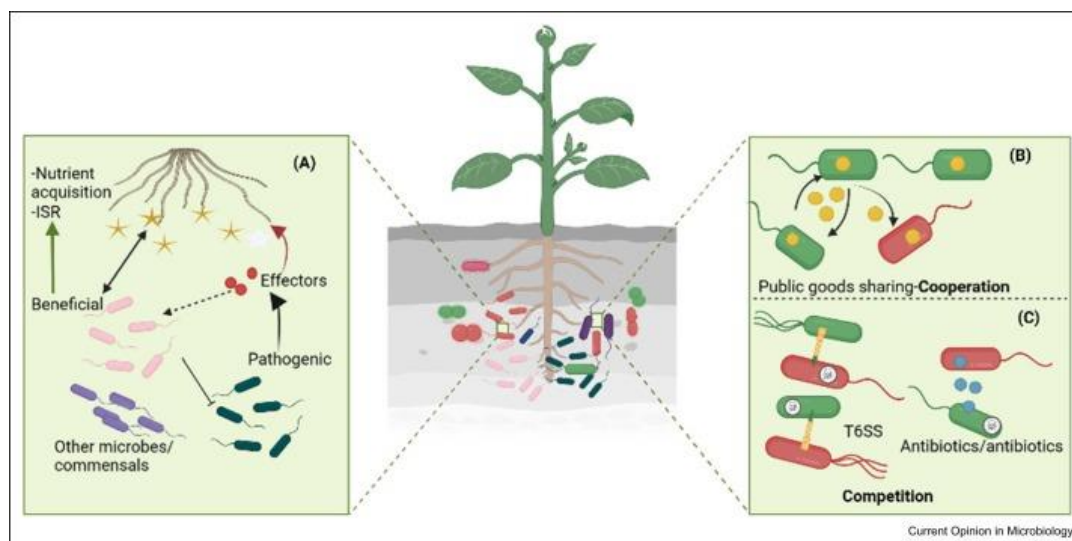


Figure 1 A graphical abstract of bacterial interactions and plant protection/health within the rhizosphere. (a) The plant releases root exudates (yellow stars) into the soil to either manipulate rhizosphere microbial community dynamics or recruit (double-ended arrow) beneficial bacteria (pink cells) after recognizing pathogen invasion. The recruited bacteria could suppress (blunt arrow) pathogenic bacteria (dark green) or ISR enhancing plant immunity as well as nutrient acquisition (green arrow). Successful pathogenic bacteria secrete effector proteins (red circles) to manipulate host immunity (red arrow) for their advantage (red arrow) and modulating microbiome compositions (dotted arrow). (b) Within the rhizosphere, where resources are deficient, bacteria cooperate to share public goods among kins (green cells). However, cheating can also occur (red cell). (c) The T6SS enables bacteria to outcompete other microbes (some of which maybe pathogenic) by killing or inhibiting their growth of target cells. Alternatively, bacteria produce antibiotics and/or bacteriocins to either kill or inhibit competing microbes (Adopted from Chepserson and Moleleki, 2023)

6.2 Root responses to flooding and poor aeration

Waterlogging or poor ventilation can cause roots to lack oxygen, impede breathing, and even lead to tissue necrosis. Flood-tolerant corn varieties can rapidly induce the formation of aerenchyma in the root cortex, thereby enhancing their adaptability in low-oxygen environments. Under waterlogging conditions, the related genes of corn (such as alanine aminotransferase, alcohol dehydrogenase, etc.) are up-regulated, which helps the root maintain energy metabolism and signal transduction, thereby enhancing survival (Kaur et al., 2021). The microbial community in the rhizosphere also changes dynamically with water conditions. Some specific bacteria (such as strains that can produce 1-aminocyclopropane-1-carboxylic acid deaminase) can alleviate waterlogging damage to the roots (Gao et al., 2023).

6.3 Climate change scenarios affecting root–soil interactions

In recent years, climate change has brought about more extreme weather. Drought, heat waves and abnormal precipitation can all have a considerable impact on the root-soil interaction of corn. When high temperatures and drought occur simultaneously, root growth is restricted, the root/stem ratio increases, and the microbial structure in the rhizosphere also undergoes reorganization. One example is that if the number of actinomycetes increases, then the number of *Pseudomonas* will decrease, having a negative impact on nutrient cycling and stress resistance (Keya et al., 2024; Swift et al., 2024; Yuan et al., 2024). In this case, corn regulates stomatal density, alters root structure, and increases signal secretions to adapt to water and heat stress (Serna, 2022; Kim and Lee, 2023). Subsequent related studies can utilize multi-omics and molecular breeding methods to screen out corn varieties with optimized root structure and stronger drought and flood resistance (Sheoran et al., 2022; Li et al., 2023; Peer et al., 2024).

7 Agricultural Management Strategies

7.1 Breeding maize for improved root traits

Root structure, root length density and root surface area are several main pursuit goals in modern corn breeding research. Through QTL mapping and genomic selection, scientists can screen out traits that efficiently absorb water and nutrients from corn (such as deeper roots, larger root biomass, more reasonable root structure, etc.)

(Karnatam et al., 2023). In a study conducted by Mu's team in 2015, it was found that enhancing root growth could improve the absorption of nitrogen in the later stage, thereby increasing yield. Deep-rooted corn not only contributes to the accumulation of soil carbon but also enhances its own stress resistance (Cotrufo et al., 2024; Sciarresi et al., 2025). These breeding efforts have also promoted the improvement of the interaction ability between roots and microorganisms, providing a genetic basis for resource utilization in low-input and adverse environments (Wild et al., 2024; Xu et al., 2025).

7.2 Fertilizer application and precision nutrient management

Precise fertilization and reasonable nutrient management are the keys to enhancing the synergy between corn roots and soil. The reasonable proportion of nitrogen, phosphorus and potassium fertilizers, combined with organic fertilizers and biochar, can improve nutrient utilization efficiency, increase yield and improve soil quality (Hu et al., 2023). Precision fertilization can also reduce nutrient loss and environmental pollution, while promoting the absorption of deep nutrients by roots (Zhang et al., 2021; Li et al., 2022). Studies have shown that the combined use of nitrogen fertilizer and biochar can increase the contents of soil organic carbon, mineral nitrogen, available phosphorus and potassium, promote root growth and nitrogen absorption, thereby significantly improving yield and nitrogen fertilizer utilization rate (Yan et al., 2023).

7.3 Soil amendments (biochar, organic matter, microbial inoculants) to enhance root–soil synergy

Biochar, organic fertilizer and microbial inoculation and other improvers can improve the physical and chemical properties of soil, regulate microbial communities and promote root-soil interaction. The combined use of biochar and organic fertilizer can increase soil pH and organic matter, enhance nutrient content, promote root growth and absorption, and also reduce the availability of heavy metals and nutrient loss (Zhang et al., 2021; Hu et al., 2023; Yan et al., 2023; Mu et al., 2025). The combined application of microbial inoculation (such as arbuscular mycorrhizal fungi) and biochar can also synergistically promote root growth, enhance stress resistance and improve nutrient acquisition, especially with obvious effects in saline-alkali land or heavy metal polluted environments (Liu et al., 2018; Hong et al., 2022; Wang et al., 2022). Long-term field experiments have shown that the combined application of biochar and organic fertilizer can significantly increase soil enzyme activity and the abundance of phosphorus-related genes, while enhancing corn yield and achieving a win-win situation of high yield and environmental friendliness.

8 Case Study: Root-Soil Interactions in Maize under Low-Phosphorus Soils

8.1 Background: phosphorus limitation as a global constraint in maize production

Phosphorus (P) is an essential nutrient element for corn. However, globally, available phosphorus in the soil is generally insufficient, which severely limits the yield. Phosphorus in the soil is easily fixed and not directly absorbed by plants, thus having a high dependence on chemical fertilizers and increasing environmental risks at the same time (Guo et al., 2024). Therefore, enhancing the adaptability of corn roots in low-phosphorus environments and their phosphorus utilization efficiency is a significant challenge for achieving sustainable agriculture.

8.2 Experimental observations (field or greenhouse-based examples):

Under low-phosphorus conditions, the root system of corn will exhibit obvious morphological plasticity. For example, it will increase the number of crown roots, enhance the density of shallow roots, prolong root length and specific root length, thereby better obtaining phosphorus in the surface soil (Chen et al., 2022; Karunarathne et al., 2023). Research has found that genotypes with a large number of crown roots tend to have higher phosphorus concentrations in leaves, faster photosynthetic rates and better yields in low-phosphorus soils.

Furthermore, reducing the proportion of root cortex living tissue (LCA) can decrease the cost of respiratory metabolism, allowing more roots to be distributed to the deep soil, thereby increasing biomass and yield. The root system also promotes the release and absorption of insoluble phosphorus by secreting citric acid and acid phosphatase (Tang et al., 2020; Bilyera et al., 2021) (Figure 2). Some low-phosphorus tolerant varieties secrete more citric acid and can absorb phosphorus more quickly, with stronger adaptability.

In terms of rhizosphere microorganisms, arbuscular mycorrhizal fungi (AMF) and phosphorus-dissolving bacteria (PSB) can synergistically enhance the activation and absorption of phosphorus. Combined vaccination can even replace some chemical fertilizers (Wahid et al., 2020; Ma et al., 2020; Khan et al., 2025). The way fertilizers are applied is also very crucial. Local deep application (such as 15 cm) or the use of high-efficiency phosphorus fertilizers (such as UP, APP) can both promote root proliferation in phosphorus-rich areas, improve absorption efficiency and yield (Wang et al., 2024; Chen et al., 2022).

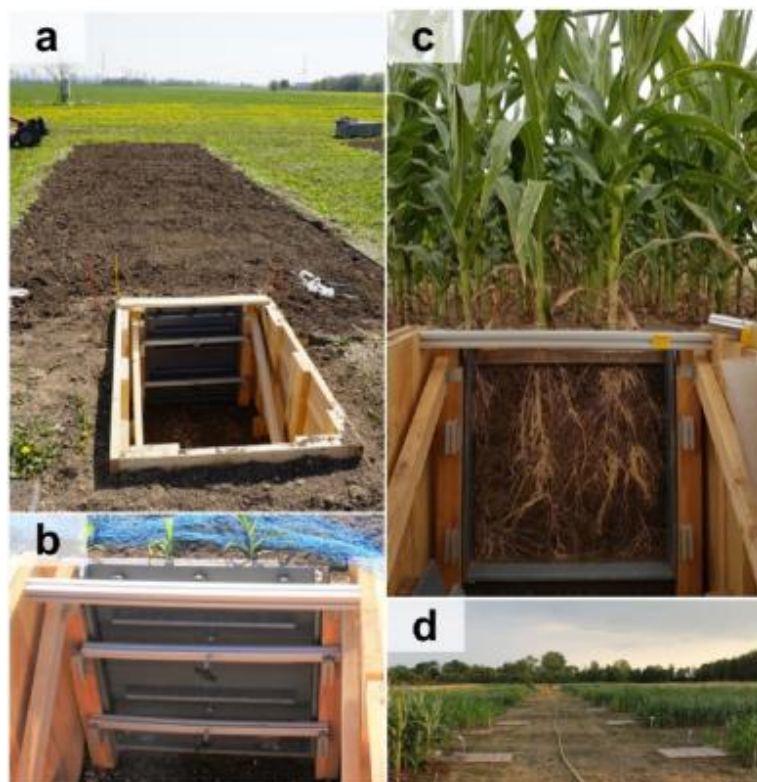


Figure 2 Custom designed root window construction at the experimental field site of the DFG priority program 2089 “Rhizosphere Spatiotemporal Organisation-A Key to Rhizosphere Functions”. (a) Experimental plot (loam) with newly installed root window construction and observation pit at the short end of the plot. (b) Close-up of the root window construction, with observation window being covered by two removable PVC boards that are pressed against the soil plot with aluminium bars and wing bolts for stability and protection against light. (c) Root window observation area (60 × 60 cm) of a loam plot planted with *Zea mays* L. wild-type (B73) at growth stage BBCH 59. (d) Root window pits covered by wooden boards in between sampling campaigns (Adopted from Bilyera et al., 2021)

8.3 Lessons learned and practical implications for sustainable maize production

During the breeding process, corn varieties with a large number of crown roots, shallow root distribution and low LCA should be given priority. Such varieties can better obtain nutrients in low-phosphorus soil and maintain a high yield (Karunaratne et al., 2023). Wang et al. (2024) pointed out after a series of research and analysis that applying fertilizers through local deep application and precise matching can significantly enhance fertilizer efficiency and reduce environmental burden. In the field of microbial management, Khan et al. (2025) conducted research on AMF and PSB, confirming that the combined inoculation of AMF and PSB can enhance the activation and utilization of phosphorus, which is a low-input and sustainable approach. Under different soil types, the adaptability of corn roots and the mechanism of phosphorus acquisition are not the same. Therefore, specific comprehensive management measures need to be formulated in combination with soil characteristics.

9 Knowledge Gaps and Future Directions

9.1 Need for integrative root phenotyping methods

At present, there are still many limitations in root phenotypic analysis. Most methods rely on destructive sampling, which is also relatively inefficient and makes it difficult to truly reflect the structure and function of field roots.

Nowadays, some new technologies are emerging, such as high-frequency capacitance method and root resistance imaging. These methods can accurately measure the volume and structure of roots in the field without damaging them, providing the possibility for large-scale dynamic monitoring. However, their applicability in different soil types and environments still requires further testing and standardization (Gu et al., 2024).

9.2 Linking root traits with soil microbiome research

The root traits of corn, such as root hairs, branches and secretions, interact with the rhizosphere microbiome. This interaction has a significant impact on nutrient acquisition, stress resistance and plant growth. Studies have found that root secretions and structures can directionally attract beneficial microorganisms and alter rhizosphere communities, thereby helping crops cope with nutrient and environmental stresses (Yu et al., 2021; Wang et al., 2024; Zhang et al., 2024). However, at present, people still have insufficient understanding of the genetic basis and regulatory mechanism of this interaction, and there is also a lack of systematic research on how they affect crop phenotypes at different scales.

9.3 Systems approaches combining genetics, soil science, and agronomy

The root-soil interaction is highly complex, thus requiring a deep integration of genetics, soil science and agronomy. Previous studies using genome-wide association analysis have found that maize genotypes can affect the rhizosphere microbiome, and some gene loci have also been found to be related to the abundance of beneficial microorganisms and crop phenotypes. However, in many cases, the physical and chemical properties of the soil have a greater impact on root-microbial interactions than the variety effect. This indicates that soil types, management methods and genetic background of crops need to be considered in combination during the research. In the future, multi-omics, systems biology and high-throughput field phenotypic platforms should be developed to combine and optimize root traits, microbiomes and agronomic measures, thereby promoting precision breeding and sustainable management (Gholizadeh et al., 2024; Zhu et al., 2024; Shi et al., 2025; Xu et al., 2025).

10 Conclusion

The interaction between corn roots and soil is a key process that determines the growth, nutrient utilization and stress resistance of crops. The root system regulates the acquisition of water and nutrients through morphological changes, the release of secretions, and the synergistic effect with soil microorganisms, while also influencing the rhizosphere environment. All these processes will significantly affect the growth and yield of corn.

Corn roots can sense and adapt to different soil conditions. The physical environment includes the compactness of the soil and the distribution of moisture, the chemical environment involves whether nutrients are easily utilized, and the biological environment is related to the microbial community. Root secretions (such as mucus, benzoxazoline, flavonoids, etc.) can improve the contact between roots and soil, reduce mechanical resistance, and also attract beneficial microorganisms, optimize the microbial community structure, and enhance nutrient absorption and stress resistance. The interaction between roots and microorganisms can also regulate soil enzyme activity and promote the cycling of key nutrients such as nitrogen and phosphorus, thereby enhancing soil health and yield. Under stress conditions such as drought, heat waves or low phosphorus levels, this dynamic synergy among roots, soil and microorganisms helps maintain the vitality and productivity of corn.

To enhance the effect of the interaction between corn roots and soil, a combination of genetics, soil science, microbiology and agronomy is required. Improving root traits through targeted breeding, applying fertilizers rationally, optimizing irrigation and soil improvement (such as biochar and microbial inoculation, etc.) can all enhance the adaptability of roots and the efficiency of resource utilization. Meanwhile, by leveraging multi-omics and high-throughput phenotypic technologies, the root-soil-microbial interaction mechanisms can be more deeply analyzed, providing support for the cultivation of high-yield, stress-resistant, and resource-efficient corn varieties.

In the future, integrating the research on root phenotypes, soil environment and microbiome, along with precise agronomic measures, will become the key to enhancing corn yield and resilience. Optimizing the interaction between roots and soil not only leads to high and stable yields but also lays a foundation for food security and sustainable agricultural development.

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Conflict of Interest Disclosure

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

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