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Analysis of the Diversity and Functional Potential of Phosphate-Solubilizing Bacteria in Acidic Tea Garden Soil

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Abstract Acidic tea garden soils generally exhibit low pH, abundant aluminum-iron oxides, and easily leachable base ions, which result in the adsorption of phosphorus on mineral surfaces or its precipitation with metal ions, thereby "fixing" the available phosphorus and keeping it in a restricted state for a long time. Faced with this bottleneck, phosphate-solubilizing bacteria promote the dissolution of inorganic phosphorus and the mineralization of organic phosphorus through secreting organic acids, chelating metals, and producing phosphatases, making them an important microbial resource for improving the efficient utilization of phosphorus in tea gardens. In recent years, high-throughput sequencing, functional gene markers (such as phoD, gcd/pqq), and metagenomics have advanced our understanding of the community structure and functional potential of phosphate-solubilizing bacteria, particularly revealing that soil acidification can significantly alter the phoD carrying community and reduce the phosphorus activation ability. Based on the analysis of the phosphorus availability limitation mechanism in acidic tea garden soils, this paper comprehensively discusses the diversity pattern, molecular mechanism, and environmental driving factors of phosphate-solubilizing bacteria, and further evaluates the selection of dominant strains, the development of microbial agents, and the requirements for ecological safety. It proposes a research prospect of multi-omics integration and precise microbial regulation.

Keywords Acidic tea garden soil; Phosphorus availability; Phosphate-solubilizing bacteria; phoD; gcd/pqq; Metagenomics; PICRUSt2; Microbial inoculant

1 Introduction

Tea plants prefer an acidic environment. The suitable pH range is generally considered to be 4.5-5.5; however, in production, long-term single application or excessive application of chemical fertilizers, strong rainfall leaching and terrain runoff processes can easily cause further acidification of tea garden soil and an increase in exchangeable aluminum and a decline in the base ion pool, thereby affecting nutrient supply and microbial processes. Comprehensive analysis of tea garden soil at the national scale indicates that more than half of the samples have a pH outside the "optimal range" for tea plants, and acidification and nutrient imbalance have become common problems restricting the construction of high-quality tea gardens (Ding et al., 2021). Tea plants also have strong tolerance to aluminum and enrichment characteristics. They can maintain growth in an acidic-aluminum environment, and the chemical environment in the rhizosphere is more prone to change, making tea gardens a typical farmland ecosystem for studying the coupling relationship of "acidification-aluminum-phosphorus-microorganisms".

The concentration of inorganic phosphorus in soil solution is usually low. A large amount of phosphorus exists in the form of mineral adsorption or precipitation, and its mobility and biological availability are determined by the dynamic equilibrium of adsorption/desorption and precipitation/dissolution (Zeng et al., 2024). Under acidic conditions, phosphorus is more likely to undergo coordination exchange with the surfaces of iron and aluminum oxides, or form insoluble compounds with Fe and Al; at the same time, soil organic phosphorus needs to be released by microbial phosphatase hydrolysis, and acidification may alter the related microbial communities and enzyme activities, thereby exacerbating the deficiency of available phosphorus (Wan et al., 2025; Zhang et al., 2025).

Phosphate-respiring bacteria (also referred to as phosphate-respiring microorganisms in a broad sense) transform difficult-to-utilize phosphorus into absorbable forms through processes such as organic acid solubilization of phosphorus, enzymatic mineralization, and metal chelation. They are considered as potential approaches to enhance crop phosphorus nutrition and reduce reliance on chemical phosphorus fertilizers (Adeyemo et al., 2025). At the functional gene level, phoD (related to alkaline phosphatase) is widely distributed in the soil and can serve as an important marker for characterizing the potential of organic phosphorus mineralization; while gcd and its related pqq gene cluster are closely related to the glucose dehydrogenase-glutaric acid pathway and are key links in the typical inorganic phosphorus dissolution mechanism (Chen et al., 2024). For acidic tea gardens, the core scientific issues have gradually focused on: whether phosphate-respiring bacteria can "stably perform" under the background of strong acid and aluminum-rich iron, how the community is constructed and maintained, whether there is functional redundancy, and the long-term impact of agent input on the local microbial network and ecological security (Wan et al., 2025).

2 Soil Characteristics of Acidic Tea Gardens and the Limiting Mechanism Of Phosphorus Availability

2.1 Phosphorus fixation and precipitation mechanism under acidic conditions

In acidic soil, the availability of phosphorus is constrained by the "surface adsorption-mineral precipitation" dual process: On one hand, phosphate ions are easily adsorbed on the surfaces of minerals with positive charges or strong coordination sites (such as Fe/Al oxides), reducing the concentration of phosphorus available for plant absorption in the soil solution; on the other hand, phosphorus can also form insoluble mineral phases with Fe and Al, or undergo co-precipitation in the microenvironment, thus entering more stable and less-released reservoirs (Jindo et al., 2023). The rhizosphere processes (root absorption, proton release, organic acid secretion) and microbial metabolism will change the local pH and ligand supply, thereby affecting the adsorption/desorption and dissolution/precipitation equilibrium (Pang et al., 2024). Therefore, the phosphorus limitation in "acidic tea gardens" is not a static deficiency but is continuously locked by geochemical processes (Yigezu et al., 2023; Pizon et al., 2025).

2.2 The effects of aluminum and iron ions on the availability of phosphorus

Aluminum and iron are the key active components that affect the availability of phosphorus in acidic soils: At low pH conditions, exchangeable Al^{3+} is more likely to be released and participate in phosphorus fixation, transferring phosphorus from the available pool to the unavailable pool; at the same time, aluminum toxicity also interferes with the absorption, transportation, and utilization of various nutrients (including phosphorus) by plants. From the microbial perspective, acidity and soluble/exchangeable aluminum may inhibit the activity of some soil enzymes (including the acidic phosphatase activity related to the phosphorus cycle) and change microbial growth and substrate utilization, thereby indirectly affecting organic phosphorus mineralization (Pang et al., 2024; Wang et al., 2025). Given that tea plants have strong aluminum tolerance and enrichment characteristics, the coupling relationship of "aluminum-microorganisms-phosphorus" in tea garden ecosystems is more complex: On one hand, aluminum promotes phosphorus fixation; on the other hand, the organic ligands released by plants and microorganisms may chelate aluminum and promote local phosphorus release (Guo et al., 2024; Scherwietes et al., 2025).

2.3 Synergistic effect of long-term fertilization in tea gardens and soil acidification

Tea gardens often apply high nitrogen intensities to enhance yield and quality. The processes such as ammonium nitrogen nitrification generating protons and nitrate nitrogen leaching carrying basic ions accelerate soil acidification. Moreover, acidification enhances the activation of Al and the fixation of phosphorus, further exacerbating the "high input-low utilization" problem of phosphorus efficiency. National-scale surveys and long-term field studies have all indicated that soil acidification in tea gardens is widespread in most production areas, and the fertilizer management method is an important driving factor (Figure 1) (Shu et al., 2025). Further, long-term nitrogen addition can reduce soil available phosphorus and induce changes in microbial communities and functional genes related to phosphorus cycling, demonstrating a chain effect of "nitrogen-driven acidification-acidification-driven phosphorus limitation-microbial response reshaping phosphorus cycling".

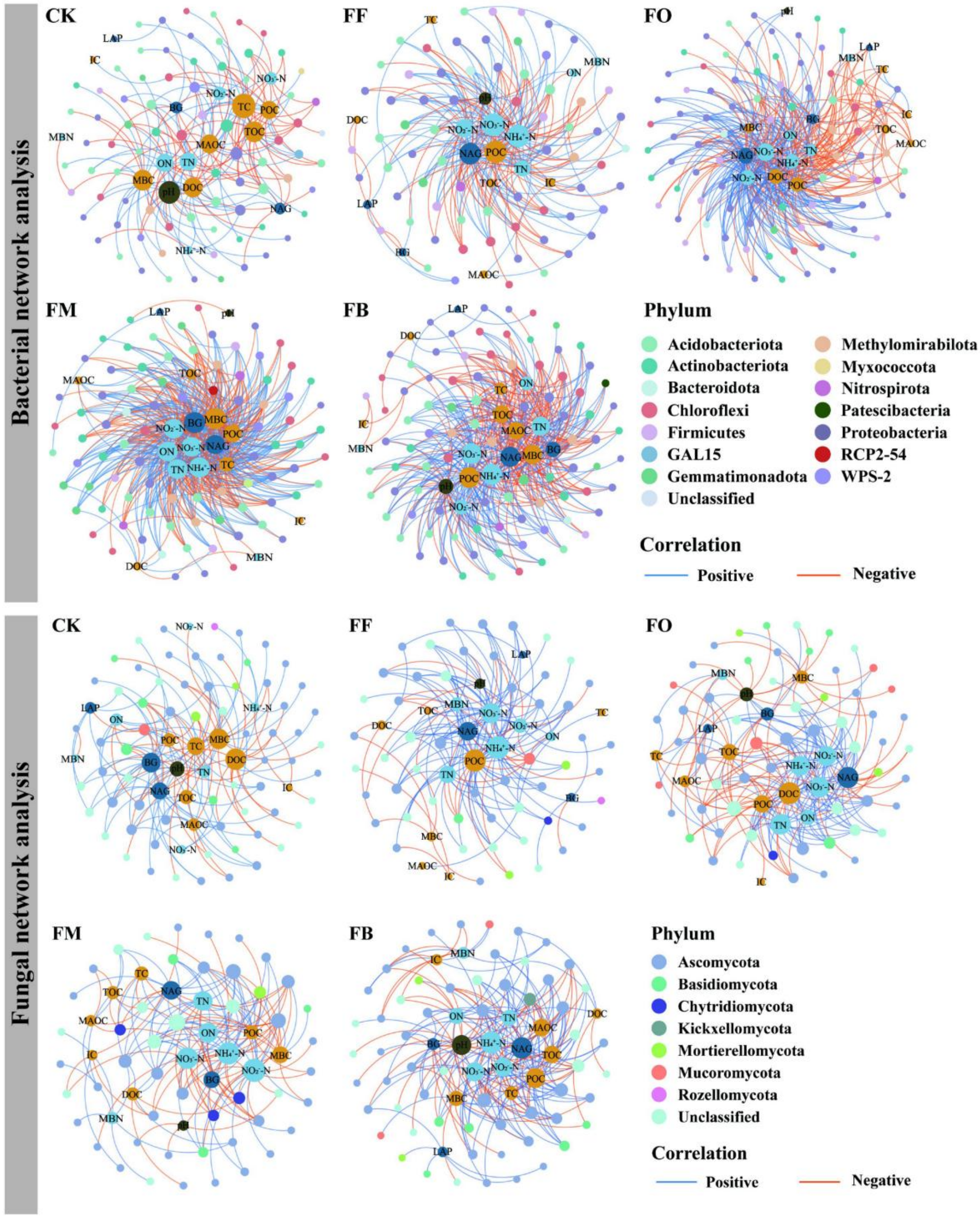

Figure 1 Network analysis of microbial communities and soil physicochemical properties under different fertilization treatments (Adopted from Shu et al., 2025)

3 Community Diversity Analysis of Phosphate-solubilizing Bacteria

3.1 Classification and functional groups of phosphate-solubilizing bacteria

Phosphate-solubilizing bacteria are not a single phylogenetic unit but a diverse collection of microorganisms with the functional phenotype of "promoting phosphorus release/mineralization" (Li et al., 2024). They are commonly found in several groups such as the Proteobacteria and Firmicutes, and may also include fungal groups (Pan et al., 2023). Roughly classified by functional processes, they can be summarized into three categories: the first is the inorganic phosphorus dissolution type, which achieves mineral phosphorus dissolution by secreting organic acids to lower pH and complexing metals such as Ca/Fe/Al; the second is the organic phosphorus mineralization type, which secretes alkaline/acidic phosphatases or phytases to hydrolyze organic phosphorus; the third is the synergistic enhancement type, which indirectly enhances plant phosphorus uptake by producing iron carriers, altering root carbon flow, or interacting with mycorrhizae, etc. Due to the fact that "the same function is shared by multiple phyla and genera", the phosphate-solubilizing function at the community level may show certain redundancy. However, whether this redundancy is sufficient to resist stress in a strongly acidic and aluminum-rich environment still needs empirical evidence (Lang et al., 2022).

3.2 Community structure characteristics based on high-throughput sequencing

High-throughput sequencing has facilitated the detailed characterization of microbial communities in tea plant root zones and soil: 16S rRNA and ITS amplicons can elucidate the bacterial/fungal community structure, while functional marker genes (such as phoD) can further focus on bacterial subgroups related to organic phosphorus mineralization. Studies on tea soil as the object indicate that the composition, abundance, and network structure of the phoD carrying community can significantly differ under different acidification levels, and are correlated with soil phosphorus components and tea yield and quality indicators (Rothenberg et al., 2022). On the other hand, short-term pot experiments with phosphorus supply also show that different phosphorus input levels can significantly alter the diversity of bacterial and fungal communities in the tea root zone, accompanied by differences in functional prediction pathways (such as carbon metabolism and phosphorus transport-related pathways), suggesting a traceable response chain between "management measures-root community-functional potential" (Lang et al., 2021; Li et al., 2024).

3.3 Mechanism of community assembly under acidic environments

At multiple environmental scales, soil pH has been repeatedly demonstrated to be a key factor in explaining the diversity and composition differences of bacterial communities: classical continental-scale studies have shown that bacterial diversity and richness can be significantly explained by soil pH, and acidic soils typically have lower diversity (Kui et al., 2021). Returning to the tea garden system, acidification not only directly alters the physiological and resource acquisition strategies of bacteria, but also indirectly shapes ecological niches by changing Al activity, phosphorus forms, and the rate of organic matter decomposition, thereby enhancing the role of environmental selection (deterministic process) in community assembly (Rothenberg et al., 2022; Nian et al., 2025). In the case of tea garden soil acidification, the phoD carrying community diversity decreases and is accompanied by changes in the relative abundance of specific taxa, as well as differences in the complexity of the co-occurrence network, all of which support the mechanism framework of "acidification driving community reorganization and functional shift".

4 Functional Mechanisms of Phosphate-Solubilizing Bacteria (Psb): Recent Evidence-based Overview

4.1 Mechanism of organic acid secretion and inorganic phosphorus dissolution

The core of inorganic phosphorus dissolution lies in "acidification + complexation": Phosphorus-depleting bacteria secrete organic acids such as gluconic acid and citric acid, which can lower the local pH, and simultaneously form carboxylate ligands to complex metal cations such as Ca, Fe, and Al, weakening the lattice stability of phosphate minerals and promoting the release of phosphorus (Leite et al., 2024). At the molecular level, the typical pathway is the periplasmic type PQQ-dependent glucose dehydrogenase (GDH) that oxidizes glucose to form gluconic acid, thereby achieving acidification of the medium and phosphorus dissolution; this process is closely related to the gcd and pqq gene clusters and can be regulated by environmental conditions such as soluble phosphorus levels (Chen et al., 2024). For acidic tea gardens, this mechanism may either promote phosphorus release or compete with processes such as aluminum chelation-re-precipitation, and the key to determining its net effect lies in the rhizosphere microenvironment and mineral components.

4.2 Analysis of phosphatase-related functional genes (such as phoD, gcd, etc.)

PhoD is often used as a molecular marker for the potential of soil organic phosphorus mineralization: Relevant studies have pointed out through genomic and metagenomic database analysis that phoD is distributed across multiple bacterial phyla and is ubiquitous in the environment and has a relatively high abundance in soil, providing a basis for community ecological research based on phoD (Dai et al., 2019). In contrast, gcd more directly points to the function of inorganic phosphorus dissolution: Metagenomic studies have shown that gcd is relatively common in soil samples, and its relative abundance can be an important factor in explaining the differences in bioavailable phosphorus, and can appear multiple copies and potential horizontal transfer signals in the genomes of different bacterial phyla (Rasul et al., 2019). Combined with the results from long-term nitrogen input studies in tea gardens, such as "soil pH has a significant direct effect on microbial phosphorus cycling, and phoD-related communities change with nitrogen application levels", it can be seen that including functional genes and environmental factors in the analysis is the key path to distinguish "changes in community composition" from "changes in functional intensity".

4.3 Metagenome and functional prediction (PICRUSt/KEGG Pathways) analysis

Metagenomes can directly obtain the functional gene profile of the community, which is suitable for analyzing the potential metabolic network of phosphate-solubilizing bacteria and processes such as phosphorus transport/ phosphorus starvation response; however, when the sample volume is large or resources are limited, the functional prediction method based on amplicon data still has practical value (Yang et al., 2025). PICRUSt proposes a "function prediction based on phylogenetic inference" prediction framework, and PICRUSt2 further expands in aspects such as placing ASVs in reference trees, gene family inference, and pathway summarization, making it a common strategy to infer KEGG homologous genes and pathways from 16S data; KEGG, as a pathway knowledge base, also provides standardized coordinates for mapping gene abundance to metabolic networks (Douglas et al., 2020). It should be emphasized that the prediction results reflect "potential" rather than "expression", and in the study of acidic tea gardens, it is necessary to try to verify the prediction results with enzyme activity, available phosphorus, phosphorus components, and key genes (phoD/gcd/pqq) measured in practice to reduce the risk of over-prediction.

5 Effects of Soil Environmental Factors on Phosphorus-Degrading Bacterial Communities and Functions

5.1 Correlation analysis of pH, organic matter and available phosphorus content

pH often becomes the dominant factor influencing the structure and function of phosphorus-degrading bacteria (especially the phoD carrying community) through multiple pathways such as influencing Al activity, mineral surface charge, and microbial physiological adaptation; organic matter determines the supply of carbon sources, the source of complexing agents, and the microbial active substrate pool, and is coupled with the phosphorus mineralization process (Hegyi et al., 2021; Jindo et al., 2023). In the study of the acidification gradient of tea garden soil, soil pH was significantly positively correlated with various active/moderately active phosphorus components, phoD gene abundance, and tea yield and quality indicators, while the increase of non-active phosphorus due to acidification suggested a consistent direction of "acidification-phosphorus pool transfer-functional group attenuation" (He et al., 2025). Short-term phosphorus supply potting experiments also showed that phosphorus input could significantly increase available phosphorus and change the diversity and metabolic pathways of rhizosphere microorganisms, indicating that available phosphorus is not only a response variable but may also participate in the feedback regulation of the community (Che et al., 2025).

5.2 The regulatory role of soil trace elements on the activity of phosphorus-depleting bacteria

Trace elements in the soil-microbe-plant system are both essential nutrients and potential stressors: metals such as Fe, Mn, Zn, and Cu participate in various enzyme systems and electron transfer processes, and may alter the efficiency of phosphorus release by influencing microbial metabolism and rhizosphere chemical reactions; in acidic soils, the toxicity of Al and the increased metal activity may inhibit microbial biomass and enzyme activity, thereby weakening the phosphorus cycling process (Asirifi et al., 2025). Recent studies have further proposed that mineral ions can enhance soil phosphorus availability through the "microbial phosphorus dissolution process" (such as zinc ions promoting microbial phosphorus dissolution and improving phosphorus utilization efficiency), providing new experimental clues for understanding the coupling of "trace elements-phosphorus dissolution mechanism" (Adeyemo et al., 2025; Barzgar et al., 2025; Chandrika et al., 2025). For tea plantations, a balance window needs to be found between "supplementing trace elements to promote metabolism" and "acidification increasing metal activity leading to stress" (Yu et al., 2024; He et al., 2025).

5.3 Multivariate statistical analysis (RDA/CCA) reveals driving factors

In community ecology research, RDA/CCA and other constrained ordination methods can explicitly link species or functional group changes to environmental gradients, facilitating the identification of key driving factors and reducing the one-sidedness of single-factor analysis (Hegyi et al., 2021). Methodologically, CCA, as a classic direct gradient analysis technique, was proposed by ter Braak and has since been widely used in community ecology; in the ecological statistics tool of R language, the vegan package provides mature implementations for cca and rda. Experientially, soil organic carbon, total nitrogen, available phosphorus, and exchangeable Ca are often identified as important factors shaping the phoD bacterial community; and the study of tea garden acidification also uses RDA to demonstrate the systematic correlations between pH, phosphorus components, phoD abundance, and tea yield and quality indicators. For the study of phosphate-solubilizing bacteria in acidic tea gardens, it is recommended to incorporate "pH-aluminum-iron activity-phosphorus component-organic matter-management measures" into the same statistical framework to obtain a more mechanistically relevant explanation.

6 Potential for the Development and Agricultural Application of Phosphate-Solubilizing Bacteria

6.1 Screening, isolation and identification of dominant phosphate-solubilizing strains

The development of superior phosphate-depleting strains is typically carried out in a stepwise manner: starting from "phenotypic screening → quantitative determination of phosphorus solubilization → genetic identification → functional verification". Using insoluble phosphorus sources (such as calcium phosphate, phosphorite powder, etc.) as selection pressure, candidate strains are identified through the measurement of the clear zone and phosphorus solubilization, and then classified and functionally annotated using 16S rRNA/whole genome (Wang et al., 2022). In studies on the rhizosphere of tea plants, there have been cases where phosphate-depleting bacterial strains were isolated from the rhizosphere soil and identified as belonging to the genus Paenibacillus, indicating that there are indeed cultivable functional bacterial resources in the tea plant rhizosphere (Guo et al., 2024). At the same time, new isolation and enrichment strategies also emphasize that environmental variables can affect the proportion of cultivable phosphate-depleting bacteria and their solubilization potential, suggesting that the screening system should try to simulate the real pH and metal background of an acidic tea garden to improve the "effective after entering the soil" screening hit rate (Pilotto et al., 2025).

6.2 The promoting effect of phosphate-respiring bacteria on nutrient absorption in tea plants

The potential value of phosphate-respiring bacteria for tea plants lies not only in increasing the available phosphorus in the soil, but also in influencing yield and quality through the "phosphorus-carbon-nitrogen metabolism-quality substance synthesis" chain (PTimofeeva et al., 2023). Potted experiments have shown that when certain phosphate-respiring bacteria are inoculated in combination with phosphate rock powder, it can increase the phosphorus absorption in the above-ground parts of tea plants and increase biomass, suggesting that they have the application prospect of promoting the effective utilization of phosphorus in acidic soil (Wahid et al., 2020; Dong et al., 2025). On the other hand, the root-associated microorganisms of tea plants exhibit diversity and plasticity in metabolic pathways in response to short-term phosphorus supply, and functional predictions indicate that some carbon-nitrogen metabolic pathways can be enhanced with the increase of phosphorus input, indirectly supporting the idea of "improving nutrient utilization by regulating microbial processes" (Enriquez-León et al., 2025). It should be noted with caution that high phosphorus input may reduce microbial alpha diversity or inhibit mycorrhizal functional groups. Therefore, the combination of "fertilizer + moderate phosphorus application" may be more in line with ecological efficiency (Wahid et al., 2020; Timofeeva et al., 2022).

6.3 Development of microbial agents and evaluation of their ecological safety

From an industrialization perspective, for phosphorus-solubilizing bacteria to move from the laboratory to the field, they must overcome two hurdles: quality standards and ecological safety (Timofeeva et al., 2022). The current national standard GB 20287-2006 of China stipulates the classification, requirements, and testing rules for "agricultural microbial agents". Among the functional groups, "phosphorus-solubilizing microbial agents" are clearly included; the standard system also emphasizes that the bacterial strains should be safe and effective, and producers are required to provide classification identification and safety evaluation materials, and to set requirements for indicators such as the effective viable bacteria count, the rate of contaminants, and the limit of heavy metals in the product. This means that in the development of tea garden phosphorus-solubilizing agents, not only the promoting effect needs to be proven, but also the stability and non-harmfulness under carrier, storage, transportation, and application conditions, as well as the long-term impact on the local microbial network, the activation of heavy metals, and ecological risks need to be evaluated (Pilotto et al., 2025).

7 Case Study: Functional Verification of Dominant Phosphate-Solubilizing Bacteria in a Typical Acidic Tea Garden

7.1 Overview of the study area and sampling design

Taking the Wuyi Rock Tea production area as an example, a study was conducted in the Wuyi Mountain region of Fujian Province. Root zone soil samples were collected from tea plants (the latitude and longitude coordinates, soil layer depth, and the operation of avoiding fertilization points were provided in the report), and samples from different tea plant varieties' root zones were used as separation sources. This reflects the typical sampling logic under the background of "acidic mountainous tea garden-yellow-red soil-high precipitation": extracting functional bacteria in the micro-environment most influenced by the root system to improve the screening efficiency (Figure 2) (Ma et al., 2025; Pokharel et al., 2025). The key points of this design lie in the uniform sampling depth and root zone definition, recording the variety and management history, and conducting simultaneous measurements of soil pH, exchangeable acidity/aluminum, available phosphorus, and organic matter, providing a baseline for subsequent explanation of "bacterial strain function-environmental adaptability".

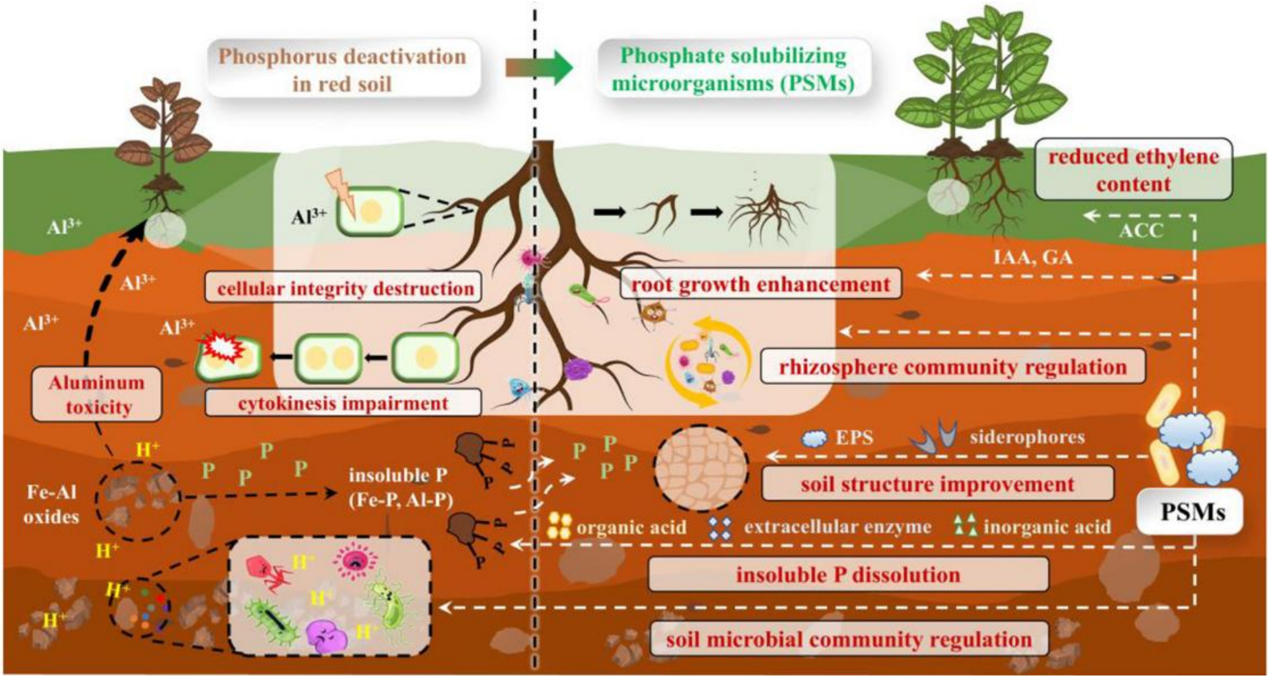

Figure 2 Schematic diagram of phosphate-solubilizing microorganisms improving red soil and crop growth (Adopted from Pokharel et al., 2025)

7.2 Selection of advantageous strains and *in vitro* verification of phosphorus-depleting capacity

In the in vitro verification stage, a combination of "solid transparent circle preliminary screening + liquid quantitative re-screening" is commonly used: first, colonies that produce obvious phosphorus-depleting rings are selected from the solid medium containing insoluble phosphorus, and then the phosphorus content is quantitatively determined using colorimetry in the liquid culture system, while simultaneously recording the pH changes in the culture medium to assist in judging the contribution of "acidification phosphorus depletion" (Joshi et al., 2023; Aguennouz et al., 2025). In the case of the root zone isolation from Wuyishan, researchers selected a small number of bacteria capable of degrading inorganic phosphorus from dozens of isolates, and preliminarily identified the advantageous strains through 16S rRNA homology comparison to the Paenibacillus genus (with high homology to known species sequences). At the same time, they reported the phosphorus-depleting capacity and the production of auxin-like substances (IAA) and other beneficial traits, presenting a "phosphorus depletion + hormone" combined promoting potential (Mahdi et al., 2020; Mpinda et al., 2024). Such results suggest that the dominant phosphorus-depleting bacteria in tea gardens may not be the few genera traditionally recognized, but may come from a broader spectrum of cultivable bacteria in the root zone.

7.3 Field experiment to verify its promoting effect on tea tree growth and phosphorus absorption

In the validation at the tea tree level, the pot experiment can assess the activation effect of the strain on insoluble phosphorus sources such as phosphate rock powder under relatively controllable conditions (Sen et al., 2024). There have been pot experiments on the acidic soil-tea tree system that used 6 phosphorus-decomposing bacteria for inoculation and set up treatments such as "whether to apply phosphate rock powder" and "different delivery methods of carriers"; the results showed that under specific treatments, the phosphorus absorption in the above-ground parts of the tea tree could reach 15.6 mg per pot, the biomass reached 10.5 g per pot, and the combination of the Burkholderia genus strain with the charcoal-based delivery system and the application of phosphate rock powder performed the best (Nhunda et al., 2024). The lesson from this case is: The effectiveness of the strain not only depends on the "phosphorus solubilization ability", but also on the carrier, rhizosphere colonization and the form of the phosphorus source (Sen et al., 2024). In the future, when promoting the use of the tea garden, the formulation of the microbial agent, the application method and the degree of soil acidification should all be optimized together.

8 Conclusions and Outlook

Based on the existing studies, the phosphate-solubilizing functional groups in acidic tea gardens exhibit a "multiple pathways and multiple genera sharing functions" pattern. Different scales of evidence can be obtained through amplicon sequencing, phoD-related functional genes, and metagenomics. However, soil acidification is often accompanied by a decrease in phoD-carrying community diversity, simplification or reorganization of the community network, and simultaneous reduction of active phosphorus components. Comprehensive analysis of tea garden soils at the national scale also indicates that acidification and nutrient imbalance are widespread, providing extensive and urgent application scenarios for the study of the diversity and ecological functions of phosphate-solubilizing bacteria.From a mechanistic perspective, dephosphorylating bacteria participate in the phosphorus cycle through multiple pathways such as "organic acid-complexation phosphorus release", "phosphatase-organic phosphorus mineralization", and "phosphorus transport and starvation response". Among them, the gcd/pqq-related pathways and the phoD-related pathways respectively point to the activation of inorganic phosphorus and the supply of organic phosphorus.

Metagenomic studies have shown that key genes such as gcd are not only widespread but may also be important factors in explaining the differences in bioavailable phosphorus among organisms. For the tea garden ecosystem, the ecological significance of dephosphorylating bacteria goes beyond "supplementing phosphorus", and lies in reshaping the phosphorus mobility in the rhizosphere under a strong fixation background, improving fertilization efficiency, and possibly indirectly maintaining the nutrient foundation for quality formation.

For the next step, we will: first, promote the multi-omics closed-loop verification of" amplicon-function prediction-metagenome-transcriptome/metabolome-enzymatic activity/isotopes", avoiding merely inferring functions based on predictions; second, incorporate acidification, aluminum-iron activity, phosphorus components and management measures into a unified causal framework (such as structural equations or path models) to analyze key leverage points; third, explore the interaction between synthetic communities (SynCom) and local microbiota, improving field reproducibility through "colonization stability + functional complementarity", and at the same time, improving the quality control and ecological safety assessment of microbial agents in accordance with national standards systems. As the research on the interaction between microorganisms and trace elements and the hot processes in the rhizosphere progresses, the precise microbial regulation of acidic tea gardens is expected to move from "screening one strain of bacteria" to "designing a functional network that is interpretable and manageable".

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Conflict of Interest Disclosure

The authors affirm 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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