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Review Article

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Harnessing the Power of Microflora Diversity: Exploring Alternative Solutions to Phosphorus Scarcity in the Soil-Plant System

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ABSTRACT

Phosphorus (P) scarcity poses a significant challenge to sustainable agriculture, impacting plant growth and crop productivity. While arbuscular mycorrhizal (AM) fungi have been extensively studied for their role in enhancing phosphorus acquisition, this review explores the potential of diverse microflora as alternative solutions. The diverse microflora groups, including rhizobacteria, actinomycetes, and cyanobacteria, contribute to phosphorus availability through various mechanisms. These microfloras produce organic acids, enzymes, and chelators that enhance phosphorus solubility and mineralization, facilitating nutrient cycling. Moreover, they promote root growth, nutrient uptake efficiency, and plant growth through the production of growth-promoting substances. Unravelling the molecular interactions between microflora and plants has provided insights into signalling pathways and genetic mechanisms governing the symbiotic association. Harnessing the power of diverse microflora offers potential benefits, including reduced reliance on chemical fertilizers, improved nutrient use efficiency, and environmental sustainability. Future research directions involve exploring unexplored microflora groups, manipulating microbial communities, and integrating microflora-based strategies with precision agriculture technologies. This review highlights the significance of diverse microflora as alternative solutions to address phosphorus scarcity and advance sustainable agricultural practices.
Keywords: Phosphorus scarcity, microflora, alternative solutions, nutrient cycling, sustainable agriculture.

INTRODUCTION

Phosphorus is an essential nutrient for plant growth and is crucial for various biological processes, such as energy transfer, DNA synthesis, and cellular signalling (Elhaissoufi *et al*., 2022; Zeng *et al*., 2022). However, phosphorus scarcity has become a significant challenge in agriculture. The availability of phosphorus in the soil is limited, and the excessive use of phosphorus fertilizers has led to environmental concerns, including water pollution and eutrophication of aquatic ecosystems (Fetahi, 2019; S. Kumar *et al*., 2021; Romanelli *et al*., 2020; Yang *et al*., 2022). The scarcity of phosphorus in agricultural systems affects plant growth and reduces crop productivity. Plants have developed various strategies to cope with phosphorus limitations, such as altering root morphology, enhancing nutrient uptake efficiency, and forming symbiotic associations with beneficial microorganisms (Etesami & Adl, 2020; Jha *et al*., 2023; Singh *et al*., 2023). However, these adaptive mechanisms are often not sufficient to overcome phosphorus scarcity, resulting in reduced crop yields and economic losses for farmers. Microflora, including bacteria, fungi, and archaea, play a crucial role in soil ecosystems and have the potential to enhance phosphorus availability to plants. These microorganisms interact with plant roots and form symbiotic relationships, such as (Li & Cai, 2021; Qi *et al*., 2022). Additionally, certain bacteria possess the ability to solubilize phosphorus from organic and inorganic sources, making it more accessible to plants. The diversity of microflora in the soil is essential for maintaining soil health and fertility. Different microorganisms have unique capabilities in phosphorus cycling and nutrient acquisition (Harman *et al*., 2021). Therefore, understanding and harnessing the potential of microflora diversity can provide sustainable solutions to address phosphorus limitations in agricultural systems (Sangwan & Prasanna, 2022; Trivedi *et al*., 2020). Despite the potential of microflora diversity in enhancing phosphorus availability, there is still a research gap in fully understanding the complex interactions between microorganisms, plants, and the soil environment(Mitra *et al*., 2022). A comprehensive review of the existing literature is necessary to synthesize the current knowledge and identify the research gaps in this field. The objective of this review are to explore the role of microflora diversity in addressing phosphorus limitations in agricultural systems. By analysing and summarizing the available research, this review aims to provide insights into the mechanisms involved in phosphorus solubilization and uptake by microorganisms, as well as their interactions with plants (Netherway *et al*., 2021). Furthermore, this review will identify the factors influencing microflora diversity and its impact on soil phosphorus availability(Zhang *et al*., 2021). Ultimately, the goal is to highlight the potential applications of microflora diversity in sustainable agriculture and propose future research directions to bridge the existing knowledge gaps.

Diversity of Microflora in Phosphorus Management

Let's have an overview of different types of beneficial microflora beyond arbuscular mycorrhizal fungi, such as rhizobacteria, actinomycetes, and cyanobacteria. The arbuscular mycorrhizal (AM) fungi are well-known for their role in enhancing phosphorus uptake by plants, there are several other types of beneficial microflora that contribute to phosphorus management in agricultural systems. Understanding the diversity and functions of these microorganisms is crucial for harnessing their potential in addressing phosphorus limitations,

Rhizobacteria: Rhizobacteria, also known as plant growth-promoting rhizobacteria (PGPR), are a diverse group of bacteria that colonize the rhizosphere-the region of soil surrounding plant roots. These bacteria establish mutualistic relationships with plants and provide various benefits, including enhanced nutrient availability. Some rhizobacteria possess the ability to solubilize phosphorus by producing organic acids and phosphatases, thereby increasing phosphorus accessibility to plants (Castagno *et al*., 2021; Sulieman & Mühling, 2021). They also promote root growth and improve nutrient uptake efficiency, contributing to overall plant health and productivity (Griffiths & York, 2020).

Actinomycetes: Actinomycetes are filamentous bacteria that are commonly found in soils. They play a significant role in phosphorus cycling and contribute to soil fertility. Actinomycetes have the capability to produce enzymes, such as phosphatases and phytases, which can hydrolyze organic phosphorus compounds and make them available for plant uptake (Zhang *et al*., 2020) . Moreover, actinomycetes exhibit antagonistic activity against soil borne pathogens, further supporting plant health and growth (Djebaili *et al*., 2020).

Cyanobacteria: Cyanobacteria are photosynthetic microorganisms that can fix atmospheric nitrogen and enhance phosphorus availability in agricultural systems. These bacteria form associations with plants in the form of cyanobacteria symbioses or biofilms on plant surfaces (Prasanna *et al*., 2021). Cyanobacteria symbioses, such as those found in rice paddies, provide a source of fixed nitrogen and contribute to the mobilization of phosphorus through the secretion of organic acids (Kollmen & Strieth, 2022). The presence of cyanobacteria in agricultural soils can significantly impact nutrient cycling and improve overall soil fertility (Rana *et al*., 2020).

The diversity of microflora beyond AM fungi presents a vast array of possibilities for managing phosphorus limitations in agricultural systems (Patwardhan *et al*., 2022). By harnessing the capabilities of rhizobacteria, actinomycetes, cyanobacteria, and other beneficial microorganisms, it becomes possible to enhance phosphorus availability, improve nutrient uptake efficiency, and mitigate the negative impacts of phosphorus scarcity on plant growth and agricultural productivity. The table 1, Shows list of different types of microflora for Phosphorus entrapment.

Table 1. Microflora for Phosphorus entrapment with their significant examples

Representing Microflora Type	Examples
Rhizobacteria	*Bacillus subtilis, Pseudomonas fluorescens, Azospirillum brasilense, Enterobacter spp.*
Actinomycetes	*Streptomyces spp., Frankia spp., Micromonospora spp., Actinoplanes spp.*
Cyanobacteria	*Anabaena spp., Nostoc spp., Oscillatoria spp., Tolypothrix spp., Gloeocapsa spp.*
Myxobacteria	*Sorangium cellulosum, Myxococcus xanthus, Stigmatella aurantiaca, Nannocystis exedens*
Phosphate-Solubilizing Fungi	*Aspergillus spp., Penicillium spp., Trichoderma spp., Mortierella spp.*
Phosphate-Solubilizing Bacteria	*Burkholderia spp., Pseudomonas putida, Bacillus megaterium, Serratia marcescens,*

	Rhizobium leguminosarum
Arthrobacter	*Arthrobacter globiformis, Arthrobacter sp. Agrobacterium tumefaciens*
Bacillus	*Bacillus subtilis, Bacillus licheniformis,*
	Bacillus cereus, Bacillus thuringiensis
Azospirillum	*Azospirillum brasilense, Azospirillum lipoferum, Azospirillum amazonense*
Streptomyces	*Streptomyces coelicolor, Streptomyces griseus, Streptomyces scabies, Streptomyces venezuelae*
Frankia,	*Frankia alni, Frankia casuarinae, Frankia elaeagni*
Nocardia	*Nocardia brasiliensis, Nocardia asteroids, Nocardia farcinica*
Clostridium	*Clostridium acetobutylicum, Clostridium butyricum, Clostridium sporogenes*
Anabaena	*Anabaena azollae, Anabaena flos-aquae, Anabaena variabilis*
Nostoc	*Nostoc commune, Nostoc punctiforme, Nostoc verrucosum*

MECHANISMS OF DIVERSE MICROFLORA CONTRIBUTE TO PHOSPHORUS AVAILABILITY AND ACQUISITION IN THE SOIL-PLANT SYSTEM

Various microflora adopts different mechanism for phosphorus availability and acquisition (Fig 1) a brief detail of them is summarized here in Table 2. including Specific names of microorganisms involved in phosphate solubilization and the mechanisms they utilize.

Phosphorus solubilization

Many microflora, including rhizobacteria, actinomycetes, and phosphate-solubilizing fungi, possess the ability to solubilize insoluble forms of phosphorus in the soil (Bargaz *et al*., 2021; Wahid *et al*., 2020). They secrete organic acids, such as citric, gluconic, and malic acids, which chelate and dissolve mineral-bound phosphorus, making them available for plant uptake(Elhaissoufi *et al*., 2022; Vera-Morales *et al*., 2023). Microorganisms, such as phosphate-solubilizing bacteria and fungi, play a crucial role in enhancing phosphorus availability in the soil. These microorganisms secrete organic acids, such as citric, gluconic, and malic acids, as part of their metabolic processes (Bouizgarne *et al*., 2023; Xu *et al*., 2023). These organic acids have the unique ability to chelate metal ions, such as calcium (Ca^{2+}) and aluminum (Al^{3+}), that are bound to phosphorus compounds in the soil. The chelation process involves the formation of stable complexes between organic acids and metal ions. By chelating these metal ions, the microorganisms make the phosphorus compounds more soluble and bioavailable for plants. Moreover, the secretion of enzymes, such as phosphatases, by these microorganisms helps to break down complex phosphorus compounds, such as phytate (myo-inositol hexa-phosphate), into simpler forms like orthophosphate (H_2PO_4- and HPO_4^{2-}) (Sarmah & Sarma, 2023). Orthophosphate, being highly soluble in water, is readily accessible for plant uptake through their root systems. This process is essential for maintaining phosphorus cycling in the ecosystem and ensuring a sufficient supply of phosphorus for plant growth and development(Mayadunna *et al*., 2023). Specific rhizobacteria residing in the rhizosphere, the region surrounding plant roots, contribute to phosphorus solubilization in the soil(Dasila *et al*., 2023). These rhizobacteria release phosphatases enzymes that hydrolyze organic and inorganic phosphorus compounds, converting them into orthophosphate, which is more easily accessible to plants. Fe examples of phosphate-solubilizing rhizobacteria include *Burkholderia cepacia*, *Pseudomonas fluorescens*, and *Rhizobium leguminosarum*. These bacteria work in close association with plant roots, enhancing phosphorus availability for the plants, and supporting their growth and development. The ability of phosphate-solubilizing rhizobacteria to improve phosphorus availability makes them valuable components in sustainable agricultural practices aimed at optimizing nutrient use efficiency(Kumari *et al*., 2023).

Mycorrhizal associations

Arbuscular mycorrhizal (AM) fungi form symbiotic associations with plant roots, extending their hyphae into the soil and increasing the surface area for phosphorus uptake (Sun *et al*., 2023). The fungi acquire phosphorus from the soil and transfer it to the plants in exchange for carbohydrates. This mutualistic relationship enhances phosphorus acquisition and improves plant growth and nutrient uptake efficiency (Doydora *et al*., 2020). Mycorrhizal symbiosis is a mutualistic association between mycorrhizal fungi and plant roots. Mycorrhizal fungi colonize the root cells of most plants and form specialized structures called arbuscular and vesicles (Xu *et al*., 2023). These structures facilitate nutrient exchange between the fungi and the plants. The hyphal network of mycorrhizal fungi extends into the surrounding soil, significantly increasing the nutrient exploration area of the plant root system.

The extensive hyphal network allows mycorrhizal fungi to access phosphorus sources that would be otherwise inaccessible to plant roots. Mycorrhizal fungi secrete various enzymes, including phosphatases, which aid in the release of phosphorus from organic matter in the soil (Song *et al*., 2021). This released phosphorus becomes available for both the mycorrhizal fungi and the associated plants, supporting their nutrient requirements.

In return for the phosphorus and other nutrients absorbed by the mycorrhizal fungi, plants provide them with carbohydrates produced during photosynthesis. This mutualistic relationship enhances nutrient acquisition for both the fungi and the plants and promotes their growth and overall health (Chen *et al*., 2021).

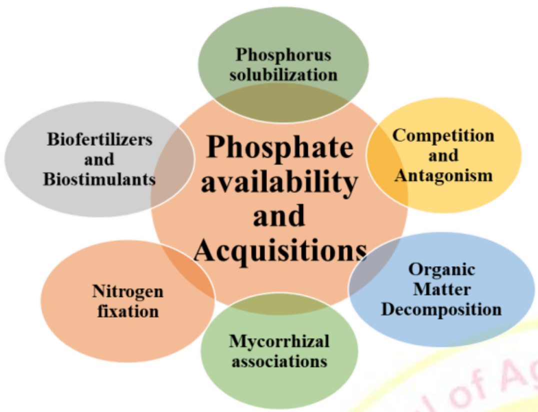

Fig 1. Mechanisms of phosphorus availability and acquisition by microflora

Nitrogen fixation

Certain microflora, such as cyanobacteria and some diazotrophic bacteria, can fix atmospheric nitrogen and convert it into plant-available forms(Wang *et al*., 2021). By providing plants with a nitrogen source, these microflora indirectly contribute to phosphorus acquisition by supporting plant growth and nutrient uptake (Bizos *et al*., 2020; Tortosa *et al*., 2023).Diazotrophic bacteria, such as those belonging to the genera *Rhizobium* and *Bradyrhizobium*, are capable of fixing atmospheric nitrogen (N_2) into a form of nitrogen that plants can use, known as ammonium (NH_4^+.This process occurs in specialized structures called root nodules in legume plants, where a symbiotic relationship forms between the plants and the nitrogen-fixing bacteria (Di *et al*., 2023). Inside the root nodules, the diazotrophic bacteria possess the enzyme nitrogenase, which catalyzes the conversion of atmospheric nitrogen into ammonium. The bacteria utilize fixed nitrogen for their own growth and metabolism. The plants, in turn, benefit from the nitrogen fixation process as they gain access to a usable form of nitrogen, which enhances their overall nutrient status (Yadav *et al*., 2023). The increased nitrogen availability positively influences the plant's growth, indirectly affecting phosphorus uptake efficiency by promoting root development and nutrient absorption capacity (Torres-Cuesta *et al*., 2023).

Organic Matter Decomposition

Microflora, including bacteria and fungi, are key players in the decomposition of organic matter in the soil. These microorganisms secrete a wide range of enzymes, such as celluloses, proteases, and phosphatases, that break down complex organic compounds into simpler forms (Alikhani *et al*., 2023). During the decomposition process, nutrients, including phosphorus, are released from the organic matter into the soil solution. This process is vital for nutrient recycling and contributes to the pool of available phosphorus that can be taken up by plants and other soil organisms (Chen *et al*., 2023). The decomposition of organic matter by microflora also contributes to soil organic matter formation, soil structure improvement, and carbon sequestration, further influencing nutrient availability and ecosystem health.

Biofertilizers and Biostimulants

Biofertilizers and biostimulants harness the potential of specific microorganisms to enhance nutrient availability and uptake in plants. Biofertilizers contain live microorganisms with specific traits, such as phosphorus-solubilizing abilities. For instance, species like *Azospirillum brasilense*, *Burkholderia* spp., and *Pseudomonas spp*. are commonly used in biofertilizers due to their ability to enhance phosphorus availability for plants (Yahya *et al*., 2022). Biostimulants, on the other hand, may not contain live microorganisms but contain substances that stimulate the growth and activity of existing beneficial microflora in the soil. For example, humic substances and seaweed extracts found in biostimulants can positively influence nutrient cycling, including phosphorus availability. The application of biofertilizers and biostimulants promotes sustainable agriculture practices by reducing the reliance on chemical fertilizers and enhancing nutrient use efficiency in plants(Aeron *et al*., 2021).

Competition and Antagonism

Microflora can influence the availability of phosphorus indirectly by competing with less beneficial microorganisms for nutrients and space in the soil environment. Bacteria such as Bacillus subtilis, Streptomyces spp., and *Pseudomonas putida* are examples of microorganisms that exhibit antagonistic behaviors towards harmful pathogens, reducing their population and indirectly benefiting plant health and nutrient uptake(Wang *et al*., 2023). Additionally, beneficial microflora can complete fewer desirable microorganisms, creating a more favorable environment for plant growth and nutrient uptake, including phosphorus. These interactions among microorganisms in the soil have profound implications for nutrient cycling, plant health, and ecosystem productivity (DERMIYATI *et al*., 2023).

MECHANISM OF CHELATION FOR PHOSPHORUS SOLUBILIZATION

Release of Organic Acids: Phosphate-solubilizing microorganisms, including certain species of bacteria and fungi, are equipped with various metabolic pathways that allow them to secrete organic acids into their surrounding environment. These organic acids, such as citric, gluconic, and malic acids, are synthesized by microorganisms as part of their nutrient acquisition and energy production processes (Amarasinghe *et al*., 2022). Encounter with Mineral-Bound Phosphorus: In soils, a significant portion of phosphorus exists in mineral-bound forms, including calcium phosphate, iron phosphate, and aluminum phosphate. These mineral-bound phosphorus compounds are not directly available for plant uptake and must be converted into soluble forms for plants to absorb(Shaked *et al*., 2023).

Chelation Process: When the organic acids secreted by the microorganisms come into contact with the mineral-bound phosphorus compounds, a chelation process is initiated. Chelation involves the formation of coordination bonds between the carboxylic acid (COOH) groups of the organic acids and metal ions (e.g., calcium, aluminum, iron) that are bound to the phosphorus compounds in the soil (Stala *et al*., 2023).

Formation of Stable Chelates: The carboxylic acid groups in the organic acids have oxygen atoms with lone pairs, which can act as electron donors to form coordination bonds with metal ions. As a result, the metal ions become surrounded and protected by the organic acid molecules, forming stable, water-soluble complexes known as chelates(Shaked *et al*., 2023).

Solubilization of Phosphorus: The chelates formed between the organic acids and metal ions are water-soluble and, therefore, mobile in the soil solution (Richardson & Simpson, 2011.As the chelates move through the soil, they can carry the metal ions and the phosphorus they were bound to in soluble form. The chelation process essentially liberates the phosphorus from the mineral-bound compounds, making it available for plant uptake(Amarasinghe *et al*., 2022).

Enhanced Plant Nutrient Availability: The soluble phosphorus in the form of orthophosphate (H_2PO_4- and HPO_4^{2-}) is now accessible to plant roots. Plants can take up the solubilized phosphorus through their root systems, thereby improving their nutrient status and promoting healthy growth and development (Iqbal *et al*., 2023). A summary of process is given in fig 2.

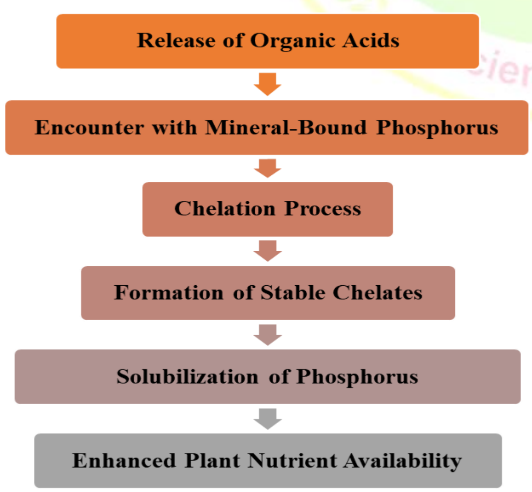

Fig 2. Mechanisms of Chelation for Phosphorus Solubilization

COMPARATIVE ADVANTAGES AND SPECIFIC CHARACTERISTICS OF VARIOUS MICROFLORA GROUPS IN PHOSPHORUS MANAGEMENT

Rhizobacteria: Rhizobacteria are versatile in their ability to promote plant growth and enhance nutrient availability, including phosphorus. They can colonize the rhizosphere, establish beneficial relationships with plants, and solubilize phosphorus through the secretion of organic acids and phosphatases (Chea *et al*., 2021). Rhizobacteria offer the advantage of being easily applicable through seed inoculation or soil application methods (M. Kumar *et al*., 2021).

Actinomycetes: Actinomycetes play a significant role in phosphorus cycling and contribute to soil fertility. They produce a wide range of extracellular enzymes, including phosphatases and phytases, which facilitate phosphorus mineralization (Oyedoh *et al*., 2023). Actinomycetes are particularly efficient in decomposing complex organic matter and releasing phosphorus, making them valuable in nutrient cycling and soil health improvement (Djebaili *et al*., 2021).

Cyanobacteria: Cyanobacteria are photosynthetic microorganisms that form associations with plants and contribute to phosphorus availability through their nitrogen fixation capabilities. They can fix atmospheric nitrogen and secrete organic acids, facilitating phosphorus mobilization in agricultural systems (Briddon *et al*., 2022). Cyanobacteria are particularly beneficial in flooded rice paddies, where they contribute to both nitrogen and phosphorus management (Afkairin *et al*., 2021).

Arbuscular mycorrhizal (AM) fungi: Arbuscular mycorrhizal fungi are well-known for their role in enhancing phosphorus uptake by plants (Etesami *et al*., 2021). They form extensive networks of hyphae that explore the soil, accessing phosphorus sources beyond the reach of plant roots (Ma *et al*., 2021). AM fungi also improve soil structure, water-holding capacity, and nutrient cycling, making them valuable contributors to sustainable phosphorus management (Püschel *et al*., 2021).

Each group of microflora has its own specific characteristics and advantages in phosphorus management, highlighting their diverse roles in enhancing phosphorus availability and acquisition in the soil-plant system. Understanding these mechanisms and comparative advantages can guide the selection and utilization of specific microflora groups in sustainable agriculture practices.

MICROFLORA-MEDIATED PHOSPHORUS MOBILIZATION AND NUTRIENT CYCLING

Mechanisms of Phosphorus Solubilization by Microflora for Organic Acids

Microflora secretes various organic acids, such as citric, gluconic, malic, and acetic acids, which play a crucial role in phosphorus solubilization (Tian *et al*., 2021). Different organic acids may have specific roles in solubilizing phosphorus from different mineral-bound forms in the soil. For example, citric acid is known to be particularly effective in chelating calcium-phosphate complexes, while gluconic and malic acids may be more effective in releasing phosphorus bound to iron and aluminum. Organic acids work by forming stable complexes with metal ions (e.g., calcium, aluminum) that are bound to phosphorus compounds in the soil. This chelation process releases phosphorus from its mineral-bound state, increasing its solubility in the soil solution (Vera-Morales *et al*., 2023). The organic acid-metal complexes are more water-soluble, making phosphorus readily available for plant uptake. Moreover, organic acids also induce a process called protonation, where they release protons (H^+) into the soil solution. This protonation further promotes the dissolution of mineral-bound phosphorus compounds, increasing the concentration of free orthophosphate ions, which can be easily taken up by plants (El Mazlouzi *et al*., 2022).

Mechanisms of Phosphorus Solubilization by Microflora for Enzymes

Microflora produces various enzymes that are involved in the hydrolysis of both organic and inorganic phosphorus compounds, making phosphorus more accessible to plants. Phosphatases are key enzymes secreted by microorganisms. Among them, acid phosphatases are particularly important in catalyzing the hydrolysis of organic phosphorus compounds, such as phytate (myo-inositol hexakisphosphate), releasing inorganic phosphate (Tian *et al*., 2021). Phosphatases act by cleaving the ester bond between the organic phosphorus compound and its associated group, liberating orthophosphate, which is available for plant uptake. This enzymatic hydrolysis breaks down complex phosphorus compounds into simpler and readily available forms. Phytases are another group of enzymes that contribute to phosphorus solubilization (Chen *et al*., 2019). These enzymes hydrolyze phytic acid, a major form of organic phosphorus found in plant tissues, seeds, and grains. By breaking down phytic acid, phytases release inorganic phosphorus, making it accessible for plant uptake.

Siderophores:

Certain microflora, particularly some bacteria, produce chelating compounds known as siderophores. Siderophores are mainly recognized for their role in iron acquisition but have the ability to form complexes with other elements, including phosphorus, thus enhancing its solubility. The specificity of siderophores for binding to particular phosphorus compounds may vary depending on the bacterial species and environmental conditions (Landa-Acuña *et al*., 2023). Some siderophores may preferentially bind to phosphorus complexes with iron, while others may be more effective in solubilizing phosphorus bound to other metal ions. The exact specificity of siderophores for different phosphorus compounds remains an area of ongoing research and may vary depending on the microbial community and soil conditions. Microflora employs various mechanisms, including the secretion of different organic acids, the production of enzymes (phosphatases, phytases, and phosphodiesterases), and the synthesis of siderophores, to solubilize phosphorus from various mineral-bound forms in the soil.

Table 2. Specific names of microorganisms involved in phosphate solubilization and the mechanisms they utilize.

Microorganism	Acidification	Chelation	Organic Acid Production	Enzymatic Hydrolysis
Pseudomonas fluorescens	✓			
Pseudomonas putida	✓			
Bacillus subtilis	✓			
Bacillus megaterium	✓			
Rhizobium leguminosarum	✓			
Rhizobium etli	✓			
Azospirillum lipoferum	✓			
Azospirillum brasilense	✓			
Burkholderia cepacia	✓			
Burkholderia gladioli	✓			
Enterobacter cloacae	✓			
Enterobacter aerogenes	✓			
Serratia marcescens	✓			
Serratia liquefaciens	✓			
Aspergillus niger		✓	✓	
Aspergillus flavus		✓	✓	
Penicillium citrinum		✓	✓	
Penicillium janthinellum		✓	✓	
Trichoderma harzianum		✓	✓	
Trichoderma viride		✓	✓	
Rhizopus arrhizus		✓	✓	
Rhizopus stolonifer		✓	✓	
Mucor circinelloides		✓	✓	
Mucor hiemalis		✓	✓	
Glomus intraradices				
Glomus mosseae				
Streptomyces griseus				✓
Streptomyces albus				✓
Actinomyces spp.				✓
Frankia spp.				✓
Frankia alni				✓

✓ indicates that the microorganism is known to utilize the corresponding mechanism for phosphate solubilization.

The diversity of these mechanisms allows microflora to efficiently access and release phosphorus, contributing to improved nutrient availability and sustainable agriculture practices (Khoshru *et al*., 2023).

FACILITATION OF PHOSPHORUS MINERALIZATION AND TRANSFORMATION THROUGH MICROBIAL PROCESSES

Decomposition of Organic Matter

Microflora, particularly actinomycetes and phosphate-solubilizing fungi, play a vital role in the decomposition of organic matter in the soil (Bhattacharyya & Furtak, 2022). Organic matter includes plant residues, animal excreta, and other organic materials in the soil. During the decomposition process, microflora secrete a wide range of extracellular enzymes that break down complex organic compounds, releasing organic phosphorus. Actinomycetes are particularly efficient in decomposing complex organic matter. These microorganisms produce a variety of hydrolytic enzymes, including cellulases, hemicellulases, and ligninases, which target the structural components of plant residues. As a result, actinomycetes break down the recalcitrant organic compounds, releasing organic phosphorus as a byproduct. Phosphate-solubilizing fungi, on the other hand, are known to be effective in decomposing organic matter and releasing organic phosphorus through their enzymatic activities. These fungi produce extracellular enzymes, such as phosphatases and phytases, which hydrolyze organic phosphorus compounds present in organic matter, releasing inorganic phosphate and making it available for plant uptake. The decomposition of organic matter by microflora contributes to the mineralization of organic phosphorus into inorganic forms, such as orthophosphate (H_2PO_4- and HPO_4^{2-}.This process ensures that the phosphorus present in the organic matter becomes accessible for plant uptake, ultimately enhancing nutrient availability in the soil (Xiong *et al*., 2023).

Phosphorus Transformation

Microflora, through their enzymatic activities, contribute to the transformation of organic phosphorus compounds into various inorganic forms. As microorganisms metabolize and recycle organic phosphorus, different inorganic phosphate compounds are formed, such as orthophosphate (H_2PO_4- and HPO_4^{2-}), pyrophosphate and polyphosphate. Enzymatic hydrolysis plays a crucial role in these transformations(Tang *et al*., 2023). Phosphatases, produced by microflora, catalyze the hydrolysis of organic phosphorus compounds, breaking them down into inorganic phosphate. For example, acid phosphatases hydrolyze organic phosphates, such as phytic acid, releasing inorganic phosphate. In addition to phosphatases, microorganisms can also carry out other enzymatic processes that contribute to phosphorus transformation. For instance, some microflora possess polyphosphate kinase enzymes, responsible for synthesizing polyphosphate from inorganic phosphate, while others may have pyrophosphates enzymes that break down pyrophosphate into inorganic phosphate. These enzymatic transformations occur as part of microbial metabolic activities and contribute to the cycling and availability of phosphorus in the soil-plant system (Pan *et al*., 2022). The diverse range of inorganic phosphate compounds formed through these microbial processes influences phosphorus availability and uptake by plants, ultimately supporting plant growth and nutrient acquisition (Ducousso-Détrez *et al*., 2022).

ROLE OF MICROFLORA IN NUTRIENT CYCLING AND ORGANIC MATTER DECOMPOSITION

Primarily, the microflora, comprising diverse groups of bacteria, fungi, and other microorganisms, play a vital role in nutrient cycling and organic matter decomposition in soil ecosystems. These processes are intricately linked to the release of bound phosphorus and its availability to plants, contributing to overall soil fertility and sustainable agricultural practices (Yan *et al*., 2023). Secondly, Synergistic Effects of Microflora on Plant Nutrient Assimilation and Utilization Efficiency here the interactions between microflora and plants have a profound impact on enhancing plant nutrient uptake efficiency, contributing to improved plant growth and productivity. Microflora influence nutrient assimilation and utilization through changes in root architecture, production of growth-promoting substances, and cooperative nutrient uptake mechanisms, resulting in enhanced nutrient acquisition and utilization efficiency (Raza *et al*., 2023).

Role of Microflora on Nutrient Cycling

Nutrient cycling is a fundamental ecological process that involves the transformation, recycling, and redistribution of essential elements in the soil (Ndlovu *et al*., 2023). Microflora, including rhizobacteria, actinomycetes, and arbuscular mycorrhizal (AM) fungi, actively participates in nutrient cycling, including phosphorus, nitrogen, and carbon. Rhizobacteria, residing in the rhizosphere, form beneficial relationships with plant roots. These microorganisms have the capability to mineralize organic nitrogen and phosphorus compounds, breaking them down into inorganic forms that can be taken up by plants (Mousavi *et al*., 2023). Their activities contribute to the release of bound phosphorus from organic matter, making it accessible for plant uptake and utilization. Actinomycetes, another group of microflora, are well-known for their ability to decompose complex organic matter, such as plant residues, animal excreta, and lignocellulosic materials. They secrete an array of extracellular enzymes, including cellulases, hemicellulases, and ligninases, which target the structural components of organic matter. Through this enzymatic breakdown, actinomycetes release nutrients, including phosphorus, back into the soil solution, enriching the nutrient pool available for plant uptake (Meena *et al*., 2023). AM fungi form mutualistic symbiotic associations with the roots of most plants. The hyphal network of AM fungi extensively explores the soil, accessing phosphorus sources that are beyond the reach of plant roots. As a consequence, phosphorus taken up by the fungi can be exchanged with the host plants, promoting nutrient redistribution and cycling in the soil ecosystem. The enhanced phosphorus uptake by plants through this symbiotic association contributes to improved nutrient availability and plant growth (Havlin & Schlegel, 2021).

Role of Microflora on Organic Matter Decomposition

Organic matter decomposition is a key process in soil ecosystems, involving the breakdown of complex organic compounds into simpler forms through the action of microflora. As organic matter decomposes, various nutrients, including phosphorus, are released from organic compounds, making them available for plant uptake and utilization (Gu *et al*., 2023). Actinomycetes, renowned for their efficient decomposition abilities, are major contributors to organic matter breakdown. These microorganisms produce a wide range of extracellular enzymes that target different components of organic matter, such as cellulose, hemicelluloses, and lignin. The enzymatic hydrolysis of these structural components releases bound phosphorus from organic compounds, further contributing to the nutrient pool available for plants. Phosphate-solubilizing fungi also play a significant role in organic matter decomposition and phosphorus release(Finore *et al*., 2023). Their secretion of enzymes, including phosphatases and phytases, aids in the breakdown of organic phosphorus compounds in organic matter. Through this enzymatic activity, phosphate-solubilizing fungi release inorganic phosphate, which becomes readily available for plant uptake. The decomposition of organic matter by microflora contributes to the release of phosphorus from organic forms and its subsequent cycling in the soil-plant system (Garraud *et al*., 2023). This process ensures that phosphorus, once locked in organic compounds, is made accessible for plant roots, supporting plant growth and nutrient acquisition.

Role of Microflora in Cooperative Nutrient Uptake

Microflora, such as rhizobacteria and mycorrhizal fungi, form symbiotic associations with plant roots, establishing mutualistic relationships that benefit both parties (Guan *et al*., 2023). Rhizobacteria, residing in the rhizosphere, interact closely with plant roots and release beneficial substances that promote plant growth and nutrient availability. For example, some rhizobacteria are capable of enhancing the availability of phosphorus, nitrogen, and other essential nutrients through various mechanisms, including the production of organic acids and enzymes (Dong *et al*., 2023). Mycorrhizal fungi, on the other hand, extend their hyphal network into the soil, effectively extending the root's nutrient exploration area. These fungi can access phosphorus and other nutrients that are otherwise beyond the reach of plant roots, facilitating nutrient uptake and transport to the host plant (Li *et al*., 2023). The cooperative nutrient uptake by microflora and plants leads to increased nutrient availability and uptake efficiency, supporting plant growth and development.

Role of Microflora in Improved Nutrient Mobilization

Microflora actively participates in the decomposition of organic matter in the soil, a process crucial for nutrient cycling and nutrient availability. Actinomycetes and phosphate-solubilizing fungi are major contributors to this process, as they secrete a wide array of extracellular enzymes (Beltran-Medina *et al*., 2023). These enzymes catalyze the breakdown of complex organic compounds, releasing bound nutrients, including phosphorus, into the soil solution. The enzymatic activities of microflora facilitate the release of phosphorus and other nutrients from organic compounds, making them accessible for plant uptake. For instance, acid phosphatases produced by microflora can hydrolyze organic phosphorus compounds, converting them into inorganic phosphate, which can be taken up by plant roots. This improved nutrient mobilization enhances the nutrient pool available to plants, supporting their nutritional needs and promoting optimal growth.

Role of Microflora in Nutrient Priming:

Certain microflora, particularly plant growth-promoting rhizobacteria, can induce nutrient-priming effects in plants. The presence of these beneficial microorganisms can trigger physiological and biochemical responses in plants, leading to enhanced nutrient assimilation and utilization efficiency. Through nutrient priming, plants become more efficient in absorbing and utilizing nutrients, including phosphorus(Beltran-Medina *et al*., 2023). This priming effect improves the plant's overall nutrient uptake capacity, enabling better nutrient utilization for growth and development. For example, rhizobacteria can trigger changes in the expression of genes related to nutrient transporters and nutrient uptake in plants, enhancing their ability to acquire and utilize phosphorus.

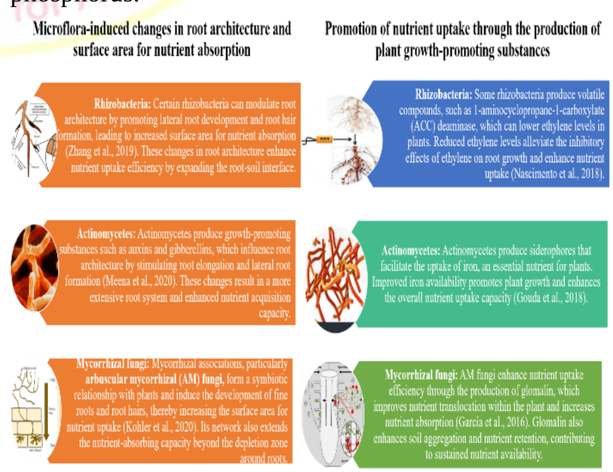

Fig 3. Enhancing Plant Nutrient Uptake Efficiency

UNRAVELLING THE MICROFLORA-PLANT INTERACTION

Signalling Pathways and molecular mechanisms underlying the symbiotic association between Plants and diverse microflora

The interaction between rhizobacteria and plants involves complex signalling pathways. For example, the recognition of specific microbial signals by plant receptors triggers a signalling cascade that leads to changes in gene expression and the activation of defence responses or symbiotic processes (Cataldi *et al.*, 2020; Pavlů *et al.*, 2018). Common signalling molecules involved in the rhizobacteria-plant interaction include nodulation factors, which promote root nodulation and nitrogen fixation. The Actinomycetes establish associations with plants through the production of plant growth-promoting substances and the modulation of phytohormones. These substances and hormones regulate various plant processes, including root development, nutrient uptake, and stress tolerance. The intricate signalling pathways involved in actinomycetes-plant interactions are still being elucidated. Furthermore, the symbiotic association between mycorrhizal fungi and plants relies on signalling molecules exchanged between the two partners(Pavlů *et al*., 2018). The plant releases strigolactones, which act as signalling molecules to stimulate fungal colonization and the establishment of mycorrhizal symbiosis (Kalia *et al*., 2021). In return, mycorrhizal fungi produce signals that enhance plant nutrient uptake and promote mutual growth benefits (Kalia *et al*., 2021; Xie *et al*., 2022) (fig 4).

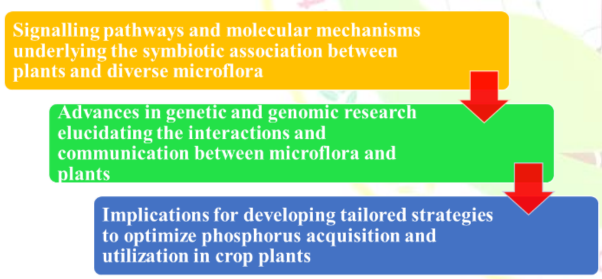

Fig 4. Unravelling the Microflora-Plant Interaction Mechanisms

Advances in genetic and genomic research elucidating the interactions and communication between microflora and plants:

Omics approaches: Recent advances in genetic and genomic research, including transcriptomics, proteomics, and metabolomics, have provided insights into the molecular mechanisms underlying microflora-plant interactions (Vidal *et al*., 2022). These techniques enable the identification of specific genes, proteins, and metabolites involved in the interaction and help decipher the communication and signalling processes between microflora and plants (Mo *et al*., 2022).

Microbiome analysis: High-throughput sequencing technologies have revolutionized the study of plant-associated microflora by enabling comprehensive microbiome analysis. By characterizing the microbial communities associated with plants, researchers can identify key microorganisms and their functional potential in promoting nutrient uptake and plant growth (Chandrasekaran, 2022; Wu *et al.*, 2022). This knowledge contributes to our understanding of the complex interactions between microflora and plants.

Implications for developing tailored strategies to optimize phosphorus acquisition and utilization in crop plants:

Targeted microbial inoculation: Understanding the signalling pathways and molecular mechanisms involved in microflora-plant interactions can inform the development of tailored strategies for microbial inoculation (Niu *et al*., 2021). Specific microorganisms that promote phosphorus acquisition and utilization can be isolated and applied as biofertilizers to enhance crop productivity. Selecting microorganisms with the ability to solubilize phosphorus, produce growth-promoting substances, or facilitate nutrient uptake can optimize phosphorus availability for crop plants (Singh *et al.*, 2019).

Genetic engineering: Insights gained from genetic and genomic research on microflora-plant interactions can be applied to crop improvement through genetic engineering (Khatri *et al*., 2023). By identifying genes involved in nutrient acquisition and signalling pathways, researchers can potentially enhance phosphorus utilization efficiency in crops (Boorboori & Zhang, 2023; Resendiz-Nava *et al*., 2023). Genetic engineering approaches may include the over expression or manipulation of genes associated with nutrient uptake or the development of improved plant-microbe communication.

SUSTAINABLE AGRICULTURE AND ENVIRONMENTAL BENEFITS

Reduced Reliance on chemical fertilizers and associated environmental risks

Nutrient supplementation: Microflora, such as rhizobacteria, actinomycetes, and mycorrhizal fungi, contribute to nutrient availability and uptake by plants. By enhancing nutrient mobilization, these microflora as reduce the need for excessive chemical fertilizer applications. This reduction in fertilizer usage decreases the risk of nutrient runoff and associated environmental pollution.

Decreased nutrient leaching: Microflora-mediated processes, such as phosphorus solubilization, organic matter decomposition, and nutrient cycling, enhance nutrient use efficiency and minimize nutrient losses through leaching. Microflora helps retain nutrients in the soil, making them more available for plant uptake and reducing the risk of nutrient runoff into water bodies.

Enhanced nutrient use efficiency and minimized nutrient losses through microflora-mediated processes:

Nutrient recycling: Microflora plays a crucial role in nutrient cycling and organic matter decomposition, which release bound nutrients and make them available for plant uptake. By facilitating the recycling of nutrients, microflora nutrient use efficiency in agricultural systems.

Phosphorus management: Phosphorus is a non-renewable resource, and its efficient use is essential for sustainable agriculture. Microflora contributes to phosphorus solubilization, mineralization, and transformation processes, enhancing their availability for plant uptake. This microflora-mediated phosphorus management improves nutrient use efficiency and minimizes phosphorus losses to the environment.

Nitrogen fixation: Some microflora, such as nitrogen-fixing rhizobacteria, can convert atmospheric nitrogen into plant-available forms, reducing the need for synthetic nitrogen fertilizers. This biological nitrogen fixation process enhances nitrogen use efficiency and reduces the environmental impact associated with nitrogen fertilizer application.

Potential applications of diverse microflora in organic and regenerative farming systems:

Organic farming: Microflora plays a significant role in organic farming systems as they contribute to nutrient cycling, disease suppression, and plant growth promotion. The use of microflora-based biofertilizers and biocontrol agents can help maintain soil fertility, reduce reliance on synthetic inputs, and support organic farming practices.

Regenerative agriculture: Microflora has great potential in regenerative farming systems, which aim to restore soil health, biodiversity, and ecosystem services. The inclusion of diverse microflora in regenerative practices promotes nutrient cycling, improves soil structure, and enhances overall soil health. Microflora contributes to the development of resilient agro-ecosystems that can mitigate climate change impacts and promote sustainable food production.

CONCLUSION

Significance in Phosphorus Cycling and Plant Nutrition

The chelation mechanism plays a vital role in the phosphorus cycle and overall soil fertility. By enhancing phosphorus solubilization, phosphate-solubilizing microorganisms contribute to nutrient cycling and availability in the soil(Vera-Morales *et al*., 2023). This process is particularly important in phosphorus-deficient soils, where the direct availability of phosphorus for plant uptake is limited. Moreover, the chelation process also influences the nutrient dynamics in the rhizosphere, the region surrounding plant roots(Marschner & Rengel, 2023). As phosphate-solubilizing microorganisms thrive in the rhizosphere, they facilitate the release of phosphorus from mineral-bound compounds, increasing the pool of plant-available phosphorus in this critical zone. Overall, the chelation mechanism of organic acids produced by microorganisms represents an essential biological process that promotes sustainable agriculture by improving phosphorus availability, plant nutrition, and overall ecosystem productivity.

Effectiveness of Different Acids in Phosphorus Solubilization:

Microorganisms, such as phosphate-solubilizing bacteria and fungi, secrete organic acids as part of their metabolic processes. These organic acids play a crucial role in solubilizing phosphorus from mineral-bound forms in the soil(Sen *et al*., 2023). One important factor influencing the effectiveness of organic acids in phosphorus solubilization is the number of carboxylic acid (COOH) groups present in the molecular structure. Organic acids with a higher number of COOH groups generally exhibit a stronger chelating capacity, allowing them to form more stable complexes with metal ions. For instance, citric acid ($C_6H_8O_7$) contains three COOH groups and is known to be a potent phosphorus-solubilizing acid. Its ability to form strong chelates with metal ions makes it highly effective in releasing phosphorus from mineral-bound compounds in the soil. Similarly, gluconic acid ($C_6H_{12}O_7$) and malic acid ($C_4H_6O_5$), both containing multiple COOH groups, are also effective in solubilizing phosphorus (Khan *et al*., 2019.On the other hand, organic acids with fewer COOH groups, such as acetic acid (CH_3COOH), may have a limited ability to chelate metal ions and, consequently, lower phosphorus-solubilizing efficiency. Apart from the number of COOH groups, the spatial arrangement of these groups in the molecular structure can also influence the acid's chelation capacity(Ahmad *et al*., 2023). The position of COOH groups affects the acid's ability to bind with metal ions effectively, further impacting its phosphorus-solubilizing potential. Overall, the solubilization of phosphorus by organic acids is a complex process influenced by various chemical interactions between the acids, metal ions, and mineral-bound phosphorus compounds in the soil.

Types of Mineral-Bound Phosphorus in Soil:

Phosphorus in the soil exists in various mineral-bound forms that are not directly available for plant uptake. These forms are part of the soil's phosphorus pool and contribute to the overall phosphorus cycling in the ecosystem(Lu *et al*., 2023).

Apatite: Apatite is a common calcium phosphate mineral found in soils. It is considered relatively insoluble, limiting its direct availability for plants. However, some microorganisms, particularly phosphate-solubilizing bacteria and fungi, have the ability to solubilize apatite through various mechanisms. By releasing organic acids and enzymes, these microorganisms facilitate the breakdown of apatite, making phosphorus available for plant uptake.

Iron and Aluminum Phosphates: In acidic soils, phosphorus can form complexes with iron and aluminum, resulting in the precipitation of iron and aluminum phosphates. These compounds contribute to the pool of mineral-bound phosphorus and may be less available to plants due to their relatively low solubility in acidic conditions.

Organic Phosphorus: A significant portion of soil phosphorus is present in organic forms, such as phytate (Myo-inositol hexa-phosphate) and other organic phosphates. These compounds are often bound to soil organic matter, and their availability for plant uptake requires enzymatic processes by microorganisms to convert them into simpler forms like orthophosphate.

Calcium Phosphates: Besides apatite, calcium can form other calcium phosphate compounds, such as dicalcium phosphate ($CaHPO_4$) and octa-calcium phosphate ($Ca_8H_2(PO_4)_6{\cdot}5H2O$.These compounds also contribute to the total phosphorus pool in the soil and may undergo solubilization processes mediated by microorganisms to enhance phosphorus availability

Readers can have a recap of the key findings and implications discussed in this review quickly. Throughout this review, we have explored the role of diverse microflora in addressing phosphorus limitations and improving sustainable agricultural practices. Key findings and implications include:

Phosphorus scarcity and its impact: Phosphorus scarcity poses a significant challenge to plant growth and agricultural productivity. Understanding the implications of phosphorus limitations is crucial for sustainable agricultural management.

The potential of microflora diversity: Microflora beyond arbuscular mycorrhizal (AM) fungi, such as rhizobacteria, actinomycetes, and cyanobacteria, have shown potential in addressing phosphorus limitations. These microflora as contribute to phosphorus mobilization, nutrient cycling, and enhanced nutrient uptake efficiency.

Mechanisms of microflora contribution: Microflora mediates phosphorus mobilization through the production of organic acids, enzymes, and chelators that enhance phosphorus solubility and availability. They also facilitate phosphorus mineralization, transformation, and nutrient cycling in the soil-plant system.

Enhanced plant nutrient uptake: Microflora induces changes in root architecture, increase the surface area for nutrient absorption, and promote nutrient uptake through the production of plant growth-promoting substances. They also exhibit synergistic effects on plant nutrient assimilation and utilization efficiency.

SIGNIFICANCE &FUTURE PROSPECTS

Such studies on the diversity of microflora give a new angle towards phosphorus scarcity and improving sustainable agricultural practices to researchers, agronomists, and policymakers seeking alternative solutions to phosphorus management. Diverse microflora offers significant potential in addressing phosphorus scarcity and improving sustainable agricultural practices. By enhancing phosphorus availability, improving nutrient use efficiency, and reducing reliance on chemical fertilizers, microflora contributes to sustainable phosphorus management and promotes environmentally friendly farming systems. Their role in nutrient cycling, organic matter decomposition, and plant-microbe interactions makes them valuable assets for optimizing phosphorus acquisition and utilization in crop plants. This review holds significance for researchers, agronomists, and policymakers involved in phosphorus management and sustainable agriculture. The comprehensive understanding of microflora-mediated processes, mechanisms, and interactions presented here provides insights into alternative solutions for phosphorus acquisition and utilization. The knowledge shared in this review can guide the development of tailored strategies, including microbial inoculation, genetic engineering, and organic farming approaches, to optimize phosphorus availability and enhance agricultural sustainability. This review serves as a valuable resource for those seeking alternative and environmentally friendly approaches to phosphorus management in agriculture.

Data Availability Statement: All data, figures and results in paper are our own and original.

CONFLICT OF INTEREST

The author here declares that there is no conflict of interest in the publication of this article.

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