



Plant Archives

Journal homepage: <http://www.plantarchives.org>DOI Url : <https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.2.092>

RHIZOSPHERE ENGINEERING FOR IMPROVED PHOSPHORUS ACQUISITION AND USE EFFICIENCY: A REVIEW

V. Mubashir Sadiq^{1*}, Deepanjali Gupta², M.S. Omji Nath³, Isha², Shubham A. Durgude⁴, Prince Kumar¹, C.K. Mohammed Salman⁵ and Shemeem Shah⁶

¹Division of Soil Science and Agricultural Chemistry, ICAR-IARI, New Delhi, India.

²Department of Soil Science, G.B Pant University of Agriculture and Technology, Pantnagr, Uttarakhand, India.

³Division of Soil Science and Agricultural Chemistry, College of Agriculture, Vellanikkara, KAU, Thrissur, Kerala.

⁴International Maize and Wheat Improvement Center, BISA, Samastipur, Bihar, India.

⁵Division of Biochemistry, ICAR-IARI, New Delhi, India.

⁶Division of Environmental Science, ICAR-IARI, New Delhi, India

*Corresponding author E-mail : msvillakkan@gmail.com

(Date of Receiving-10-06-2025; Date of Acceptance-24-08-2025)

ABSTRACT

Phosphorus (P) is essential for plant growth but frequently unavailable in soils by fixation, resulting in low uptake efficiency and environmental loss. Rhizosphere engineering—management of plant–microbe–soil relations by targeting—provides a green approach to maximize P acquisition and utilization efficiency (PUE). This review discusses progress in microbial inoculation, mycorrhizal symbiosis, soil amendment, root exudate management, crop diversification, and genetic enhancement of root characteristics. We emphasize synergies among biochar, nanofertilizers, and beneficial microbes; optimum plant genotypes with enhanced root architecture and exudation; and precision nutrient delivery systems. Challenges are the complex nature of rhizosphere processes, scalability, and long-term ecological effects. Opportunities for the future are in putting multi-omics, microbiome engineering, and field-scale application protocols together. Rhizosphere engineering can enhance crop yields, limit reliance on fertilizers, and avoid environmental losses, making it a critical innovation in sustainable phosphorus management.

Key words : Rhizosphere engineering, phosphorus use efficiency, sustainable agriculture, plant–microbe interactions.

Introduction

The quest for sustainable agriculture has gained momentum in the past few years with the imperative issues of global food security, environmental degradation, and resource limitation (FAO, 2021). In this context, the rhizosphere, i.e., the root-altered soil zone, has emerged as a priority research area for new-generation agricultural solutions. Rhizosphere engineering is a nascent science and has the potential to be a feasible solution to one of agriculture's most recalcitrant issues: phosphorus (P) acquisition and utilization efficiency. Phosphorus is a key macronutrient for plant growth and development. However, in soils, its availability is often limited by low solubility, fixation and rapid immobilization, leading to

inefficient use by plants. Phosphorus (P)—a ubiquitous macronutrient—plays a key role in plant physiology, but soil bioavailability is limited by fixation to iron, aluminum, and calcium minerals (Shen *et al.*, 2011). Traditional P fertilizers are inefficient with only ~15–30% uptake in the first season and are a cause of environmental issues such as eutrophication (Cordell *et al.*, 2009; Withers *et al.*, 2014).

Rhizosphere engineering is a paradigm shift in phosphorus management by leveraging the intricate interactions involving plant roots, soil microbes, and physicochemical processes within the rhizosphere (Zhang *et al.*, 2022). Through modulation of such interactions, researchers and agronomists attempt to optimize

phosphorus uptake by plants and optimize its use efficiency to minimize external phosphorus application and its resulting environmental effects. Root exudates are key to regulation of soil microbial communities, e.g., symbiotic mycorrhizal fungi and solubilizing bacteria, which aid in phosphorus mobilization and plant uptake. In addition, breakthroughs in molecular biology, omics technology, and bioinformatics have elucidated the genetic architectures controlling plant-microbe interactions in the rhizosphere. In addition to biological interventions, rhizosphere engineering also involves new soil management practices to construct phosphorus-enriched microenvironments in the vicinity of plant roots. Approaches like the use of biochar, microbial inoculations, and precision nutrient delivery systems enable localized nutrient delivery, reducing nutrient loss and improving plant access to phosphorus (Lu *et al.*, 2014; Wang *et al.*, 2022; Chen *et al.*, 2024). Effective application, however, hinges on collective action among researchers, farmers, policymakers, and industry players to surmount the technical, economic and socio-cultural challenges and unlock the full potential of rhizosphere engineering globally.

Rhizosphere

The rhizosphere is a limited soil zone in immediate contact with plant roots and is an important hub for various microbial activities (Marschner, 1995; Hinsinger, 2001). The zone is crucial in plant nutrient uptake since the prime interface between roots and soil. Rhizosphere, as the soil that comes into contact with the plant roots, is a dynamic system consisting of various essential components that are interrelated to each other, thereby influencing plant development, nutrient cycling, and soil health. They include plant roots, soil and microorganisms (Hinsinger, 2001; Shen *et al.*, 2011).

The rhizosphere may be divided into distinct areas that are based on proximity of roots and the number of interactions between microbes and roots. The subdivisions identified include the ectorhizosphere, endorhizosphere, and rhizoplane:

Ectorhizosphere : refers to the outer soil layer that covers plant roots, extending from the root surface to the distance to which root exudates are dispersed in the surrounding bulk soil.

Endorhizosphere : It is the innermost soil zone in direct contact with the plant roots, from the root surface to the root vascular tissue.

Rhizoplane : describes the direct contact that occurs between the plant's root surface and the surrounding ground, with the direct contact between soil particles and

root tissue (Dakora and Phillips, 2002).

Rhizosphere engineering

Rhizosphere engineering is the intentional alteration or regulation of the rhizosphere, for increased plant growth, nutrient uptake, and ecosystem function (Zhang *et al.*, 2022). Rhizosphere engineering is a nascent discipline aimed at maximizing the rhizosphere's functioning - by strategic interventions intended to stimulate positive interactions between plants and soil microorganisms, increase nutrient cycling and optimize soil condition. The main objective of rhizosphere engineering is the creation of sustainable agricultural systems that optimize crop yields and reduce associated environmental pressures like nutrient runoff, erosion, and greenhouse gas emissions.

Key components of rhizosphere engineering

Rhizosphere engineering involves an ensemble of multidisciplinary practices designed to maximize the soil-plant-microbe interface to improve nutrient acquisition, most notably phosphorus (P), and increase crop productivity and sustainability in general. The central elements of this strategy are microbial engineering, soil amendments, and plant engineering (Fig. 1). Microbial engineering entails the manipulation or addition of beneficial microorganisms for phosphorus solubilization and uptake optimization within the rhizosphere. Soil amendments, including biochar, organic matter and nanofertilizers, enhance phosphorus dynamics through improved soil structure, nutrient availability and microbial activity. Plant engineering involves genetic crop improvement for better root architecture, exudation patterns, and transporter expression to improve the plant's access and utilization of phosphorus in an efficient manner. These elements together provide an integrated rhizosphere engineering framework to enhance phosphorus use efficiency in sustainable agricultural systems.

Microbial engineering

Microbial engineering in the rhizosphere entails site-specific modification of the beneficial microbial populations—phosphate-solubilizing bacteria (PSB), arbuscular mycorrhizal fungi (AMF), and plant growth-promoting rhizobacteria (PGPR)—to enhance nutrient solubilization and mineralization. Microbial consortia can be engineered or synthetic microbial communities can be implemented for improving these major functions like phosphorus solubilization, production of organic acids, and enzymatic activities (Backer *et al.*, 2018; Meng *et al.*, 2024). Recent breakthroughs have also made it possible to create genetically engineered microbial inoculants with

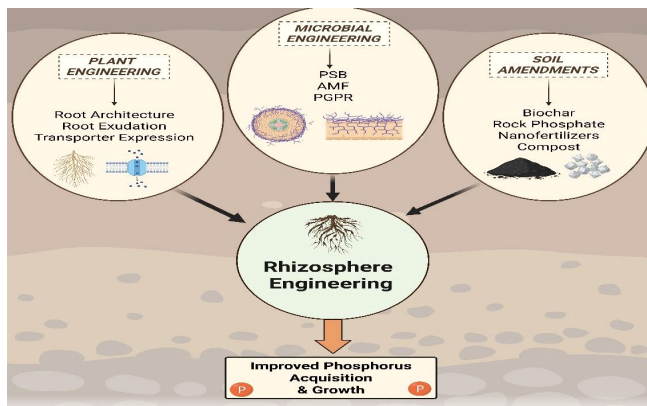


Fig. 1 : The core components rhizosphere engineering.

microbial inoculants or nano-fertilizers (e.g., nano-rock phosphate) has been reported to enhance P mobilization and uptake under both controlled and field conditions (Yasmeen *et al.*, 2022).

Plant Engineering

Plant engineering exploits the breakthroughs in molecular biology, quantitative genetics, and genome editing to create crop genotypes with high root qualities that are favorable for P uptake (Table 1). Such qualities are enhanced root biomass, longer and denser root hairs, more lateral root growth, and higher exudation of organic acids and phosphatases (Lambers *et al.*, 2006; Aono *et*

Table 1 : Plant traits relevant to rhizosphere engineering for phosphorus uptake.

Trait	Description	Engineering Strategy	Impact on Phosphorus Uptake	References
Root architecture	Deep roots, increased root length and surface area	Conventional breeding, marker-assisted selection	↓ Soil exploration, ↓ contact with P-rich zones	Lambers <i>et al.</i> (2006); Hopkins <i>et al.</i> (2014)
Root hair development	Longer and denser root hairs	QTL mapping, transgenic approaches	↓ P uptake in low-P soils	Ma <i>et al.</i> (2012); Aono <i>et al.</i> (2021)
Organic acid exudation	Exudation of citric, malic, oxalic acids	Overexpression of metabolic genes	↓ Solubilization of bound P (e.g., Al-P, Fe-P, Ca-P)	Khashi <i>et al.</i> (2021); Wang <i>et al.</i> (2023)
Phosphatase enzyme production	Release of acid and alkaline phosphatases	CRISPR/Cas gene editing, synthetic biology	↓ Hydrolysis of organic P compounds	Shulse <i>et al.</i> (2019); Chen <i>et al.</i> (2024)
Phosphorus transporter expression	High-affinity P transporter genes (e.g., OsPT2, OsPT4)	Hormonal regulation ethylene/cytokinin), genetic editing	↓ P uptake under low-P conditions	Zulfiqar <i>et al.</i> (2021)

the ability to produce high-efficiency phytases or phosphatases, designed to mobilize recalcitrant P pools (Shulse *et al.*, 2019; Gao *et al.*, 2024). Additionally, microbiome engineering approaches—such as host-mediated microbiome selection—are under investigation to utilize naturally co-evolved microbial assemblages for long-term sustainability (Zhang *et al.*, 2022).

Soil amendments

The addition of soil amendments is an elementary aspect of rhizosphere engineering to improve soil physical, chemical, and biological characteristics. The addition of organic matter (compost, vermicompost), biochar and rock phosphate not only adds vital nutrients but also changes the pH of the rhizosphere, improves microbial activity, and raises cation exchange capacity (Sui *et al.*, 2022; Zhang *et al.*, 2025). New research has confirmed that biochar amendments can increase soil enzymatic activities (e.g., alkaline phosphatase) and the number of microbes that contribute to P cycling (Borno *et al.*, 2018; Chen *et al.*, 2024). The combined use of biochar with

al., 2021). Recent studies have concentrated on modulating root exudate composition by transcriptional reprogramming or CRISPR-mediated editing to enhance genes related to rhizosphere signaling and nutrient mobilization (Wang *et al.*, 2023). Additionally, transgenic strategies have allowed the overexpression of MtPAP1 and MtPHY1 genes to facilitate enhanced phytate hydrolysis and enhanced P acquisition from organic pools (Ma *et al.*, 2012). Integration of such plant characteristics with compatible microbial companions by “holobiont engineering” is a frontier for rhizosphere optimization (Tian *et al.*, 2022).

Phosphorus dynamics in the rhizosphere-plant continuum

Phosphorus dynamics in the rhizosphere-plant continuum have been defined as complex processes and interactions of phosphorus (P) in the soil, rhizosphere, and plant roots. Phosphorus dynamics in the rhizosphere-plant continuum have a central function in regulating the availability and uptake of nutrients, thus impacting plant

growth and ecosystem productivity. The rhizosphere, which is the region of soil directly impacted by root exudates and processes, is a phosphorus transformation hotspot (Shen *et al.*, 2011). Root exudates, which include organic acids, enzymes and other substances, actively mobilize phosphorus by facilitating its desorption and solubilization from minerals in the soil (Shen *et al.*, 2011; Sui *et al.*, 2022; Peng *et al.*, 2022). Simultaneously, microbial populations resident in the rhizosphere plays an important role in phosphorus dynamics through processes of mineralization, immobilization and hydrolysis of organic phosphorus. In addition, the rhizosphere domain affects phosphorus sorption-desorption reactions since root activity creates pH changes and redox conditions, affecting phosphorus availability. Nevertheless, phosphorus excess leads to nutrient imbalance and environmental issues, prompting a need for insight into the complex dynamics in the rhizosphere-plant continuum. It is important to understand its dynamics in the rhizosphere-plant continuum for maximization of nutrient uptake efficiency and sustainable crop production (Tian *et al.*, 2022; Sui *et al.*, 2022; Peng *et al.*, 2022)

Why do we need rhizosphere engineering?

Rhizosphere engineering is gaining acceptance as an essential strategy to help solve many of the urgent issues in agriculture, environmental conservation, and food security. Below are some reasons why rhizosphere engineering is essential:

- **Maximum nutrient uptake:** Rhizosphere engineering enables us to control the populations of microbes within and around plant roots to optimize nutrient availability and uptake. This is important in enhancing crop yields, particularly in soils with low nutrients (Khan *et al.*, 2014).
- **Improving plant health:** By regulating the rhizosphere environment, we can favor the development of beneficial microorganisms that support plant health. This can result in less frequent occurrence of plant diseases and pests and ultimately enhance crop yield and quality (Lehmann *et al.*, 2011; Singh *et al.*, 2022)
- **Less dependence on chemical inputs:** Provides alternative strategies to minimize the use of chemical inputs by tapping natural processes, including biological nitrogen fixation, cycling of nutrients, and suppression of diseases, within the rhizosphere (Hakim *et al.*, 2021; Negi *et al.*, 2022).
- **Soil structure enhancement:** It may enhance soil structure by inducing the roots of plants to

secrete organic compounds, which further initiate microbial activity and soil aggregation (Kuzyakov and Razavi, 2019).

- **Environmental impact mitigation:** By encouraging effective agricultural practices, rhizosphere engineering can reduce the environmental impact of agriculture and conserve natural resources for generations to come (Withers *et al.*, 2014).
- **Meeting global food demand:** Rhizosphere engineering presents a potential pathway for realizing this vision by optimizing the use of nutrients and improving crop yields in sustainable ways (Ferreira *et al.*, 2024).

Ways of rhizosphere engineering?

Rhizosphere engineering encompasses a range of approaches aimed at manipulating the interactions between plant roots, soil microorganisms and physicochemical processes within the rhizosphere. Here are some key approaches for rhizosphere engineering:

Microbial inoculation : Targeted microbial inoculation for manipulating the activity and composition of soil microbial communities is a prospective rhizosphere engineering approach to enhance phosphorus use efficiency (PUE). It entails introducing beneficial microorganisms into soil to form symbiotic or associative relationships with plants, thus improving nutrient uptake (Meng *et al.*, 2024). One significant approach involves co-inoculation of arbuscular mycorrhizal fungi (AMF) with phosphate-solubilizing bacteria (PSB), which has proven high potential in maize-wheat production systems. Experiments conducted in the field by Haokip *et al.* (2019) found that dual inoculation enhanced soil Olsen-P by up to 20% and grain phosphorus uptake by 41% over uninoculated controls, even allowing for a 50% decrease in recommended phosphorus fertilizer application. These were caused by synergistic solubilization of applied and native phosphorus and acidification of the rhizosphere. In a related study, Emami *et al.* (2020) noted that co-inoculating wheat with rhizospheric (R185) and endophytic (E240) PSB strains resulted in improved phosphorus acquisition efficiency (PAE) and phosphorus utilization efficiency (PUE), with grain phosphorus content improving by up to 16.3% and P efficiency indices by 59% under phosphorus-deficient conditions. These results highlight that co-inoculation of functionally heterogeneous microbial strains may be superior to single inoculation in exploiting multiple, complementary mechanisms to enhance phosphorus availability and uptake by plants.

Mycorrhizal Symbiosis : Mycorrhizal symbiosis is an important rhizosphere engineering mechanism for phosphorus use efficiency (PUE) enhancement by establishing mutualistic relationships between mycorrhizal fungi and plant roots. Fungi provide an expanded effective root surface area, enhancing the plant to utilize immobile phosphorus in the soil (Etesami *et al.*, 2021). Rhizosphere manipulation has involved direct inoculation with mycorrhizal fungi or the use of crop genotypes that form effective mycorrhizal associations. For example, Thioub *et al.* (2019) illustrated that soybean inoculation with *Glomus mosseae* under low-phosphorus levels led to a 50% boost in both phosphorus uptake and PUE in comparison with non-inoculated controls. This improvement was related to enhanced phosphorus availability, higher grain P content, increased root colonization, and greater biomass accumulation. These results make mycorrhizal technologies look like potential sustainable and effective ways of improving phosphorus acquisition and use in legume-based cropping systems.

Soil Amendments : Soil amendment application is an important rhizosphere engineering practice for the purpose of enhancing soil structure, phosphorus availability, and water holding capacity, thus boosting phosphorus use efficiency (PUE) (Tian *et al.*, 2022; Sui *et al.*, 2022; Chen *et al.*, 2024; Zhang *et al.*, 2025). Organic matter, biochar, and mineral or nanofertilizers are some of the amendments that can alter the physicochemical and biological features of the rhizosphere to promote phosphorus mobilization. For example, Yasmeen *et al.* (2022) showed that the integration of encapsulated nano-rock phosphate (ENRP) with phosphate-solubilizing bacteria (PSB) in maize increased grain P uptake by 35.5% and enhanced PUE by 1.86 kg DM/kg P over uninoculated treatments. This enhancement was attributed to elevated root carboxylate exudation, reduced rhizosphere pH, and increased bioavailable pools of P (e.g., citrate-P and enzyme-P), evincing the synergistic potential of nanotechnology and microbial inoculants. Also, Borno *et al.* (2018) noted that biochar produced from rice husk and oilseed rape residues increased alkaline phosphatase activity and enhanced root and shoot P uptake in maize. Significantly, oilseed rape biochar had almost doubled phosphatase activity and greatly increased total uptake of P, even without P fertilizer application. These findings highlight the promise of biochar amendments to enhance microbial P cycling and boost phosphorus availability, providing a sustainable means of enhancing P efficiency in cropping systems.

Root exudate management : Control of rhizodeposition—a release of root exudates—is one of

the central aspects of rhizosphere engineering to improve phosphorus use efficiency (PUE). Alteration in composition and amount of these exudates may determine nutrient solubilization and microbial processes within the rhizosphere. It may be carried out through genetic modification, plant breeding, or treatment with exogenous compounds inducing favorable exudation patterns (Lambers *et al.*, 2006; Aono *et al.*, 2021). For instance, Khashi *et al.* (2021) showed that root exudates in tomato-onion intercropping systems significantly promoted phosphorus solubilization from soil-fixed forms like Al-P and Ca-P, especially when root barriers were not present. This was linked to elevated microbial activity and enhanced rhizosphere interactions, highlighting the significance of plant-plant and plant-microbe signaling in the mobilization of P. Concurrently, artificial exudate additions—glucose and alanine—activated microbial phosphorus mineralization and phosphatase activity 4- to 6-fold, as indicated by ^{33}P isotopic tracing. Such results indicate that the targeted modulation of root exudate profiles via biological or chemical means presents a promising approach for enhancing microbial-mediated P cycling, particularly in non-mycorrhizal systems (Goodey and Eshariah, 2025).

Crop diversification : Implementation of crop rotation and cover cropping in agricultural systems is a powerful rhizosphere engineering tool for enhancing phosphorus use efficiency (PUE). Diversified cropping systems promote soil biodiversity, enhance organic matter input, and facilitate nutrient cycling via nitrogen fixation and root exudation (Drinkwater and Snapp, 2007). Phosphorus cycling in the rhizosphere can be affected remarkably by diversification practices such as intercropping and rotation with legumes. For example, Zhang *et al.* (2020) indicated that maize-faba bean intercropping resulted in greater shoot biomass and phosphorus acquisition than maize monoculture or maize-maize intercrops. This improvement was attributed to faba bean root foraging behavior and acid phosphatase exudation, which enhanced phosphorus solubilization within the common rhizosphere. These findings point to intercropping as a sustainable and eco-friendly approach for increasing P availability and acquisition through synergistic plant-plant interactions.

Genetic improvement : Genetic manipulation and breeding have strong options for rhizosphere engineering to improve phosphorus use efficiency (PUE). Through the cultivation of crop varieties with better root attributes—such as greater biomass, root density, and exudation—these technologies maximize nutrient uptake and adaptation to nutrient-poor situations (Hopkins *et al.*,

2014). For instance, Ma *et al.* (2012) genetically transformed white clover through the introduction of MtPHY1 and MtPAP1 genes, leading to a considerable increase in root phytase and phosphatase activity. The transgenic lines contained as much as 2.6 times more phosphorus from organic sources such as phytate and retained more than 80% of the biomass under inorganic phosphate (Pi) treatment. Also, Shulse *et al.* (2019) utilized synthetic biology to modify root-colonizing *Pseudomonas* and *Ralstonia* species with varied phytase genes, and these drastically enhanced phytate solubilization and enhanced the growth of *Arabidopsis* in Pi-deficient conditions. Zulfiqar *et al.* (2021) also emphasized how ethylene signaling regulated phosphorus transporter genes (OsPT2 and OsPT4) in rice in another study. Ethylene, as ACC, increased these transporters under P-deficient conditions, with cytokinin as an inhibitor. These results highlight the promise of genetic and molecular technologies such as plant genome alteration, microbial biotechnology and hormonal control as novel strategies to maximize phosphorus uptake from inorganic and organic forms.

Limitations of rhizosphere engineering :

Rhizosphere engineering, though promising great potential in the case of agriculture and the environment, is not without constraint. One major limitation lies in the intricate nature of the interactions within the rhizosphere itself. The number of microorganisms, plant roots, and soil particles present is so great that it produces a dynamic and complex ecosystem, one that can be difficult to fully comprehend and control with the desired effectiveness (Vishwakarma *et al.*, 2020). In addition, limitations exist with the long-term sustainability of rhizosphere engineering applications. The input of external agents, like microbial inoculants or amendments, into the soil has the possibility of changing its original balance and hence possibly destabilizing indigenous microbial communities. The disruption can have unforeseen effects, such as compromised fertility in the soil or enhanced vulnerability to pathogens and pests in the long term (Alzate *et al.*, 2024). An important limitation is also the scalability of rhizosphere engineering methods. Although, effective results have been shown in controlled lab or small-scale field experiments, exporting them to large agricultural environments is a challenge (Vishwakarma *et al.*, 2020). Furthermore, the efficacy of rhizosphere engineering to solve larger environmental challenges, including soil erosion or climate change mitigation, could be restricted by outside factors that are not within the purview of root-microbe interactions. For example, the effect of land management, land use change, and global climatic trends

may dominate the localized impacts of rhizosphere manipulation.

Conclusion

Rhizosphere engineering is a very innovative strategy for phosphorus acquisition as well as increasing its utilization efficiency in agricultural production systems. By manipulating root-microbe interaction and soil attributes, this strategy provides optimal solutions for mitigating the problems of phosphorus deficiency and environmental contamination due to overuse of fertilizers. The utilization potential of microbial biofertilizers can provide a sustainable method for increasing P availability in the rhizosphere. By promoting symbiotic association between plants and favorable microorganisms, including mycorrhizal fungi and phosphate-solubilizing bacteria, rhizosphere engineering makes phosphorus more efficiently available in the soil to the plants. It is important to comprehend the intricate relationship between roots and soil microorganisms for the formulation of effective rhizosphere engineering. This process can also reduce nutrient runoff and alleviate environmental deterioration through enhanced phosphorus uptake and utilization efficiency, making it an important component of sustainable agriculture. Genetic engineering and nanotechnology offer new technologies for creating rhizosphere engineering approaches. Uptake of rhizosphere engineering is potentially very promising in delivering food security, sustainability to the environment, and global phosphorus challenge resilience.

Future line of work

Under the aspect of rhizosphere engineering for phosphorus uptake and its utilization efficiency, future research activities need to focus on some major directions to drive this novel approach ahead. Omics techniques (genomics, transcriptomics and proteomics) must be employed to develop knowledge on the mechanisms of P acquisition and utilization in the rhizosphere (Dasila *et al.*, 2023). In addition, there is a pressing need to maximize microbial consortia for higher phosphorus mobilization and plant delivery. This includes taking advantage of microbiome research advances to discover and redesign microbial strains with higher phosphate-solubilizing activities, in addition to understanding synergistic interactions among complex microbial communities (Cheng *et al.*, 2023). Scaling up rhizosphere engineering methods from laboratory research to field-scale agricultural application is another key area of future work (Pathak *et al.*, 2024). This will involve optimizing application protocols and evaluating economic feasibility. This includes examining impacts on soil health, microbial

community composition, and ecosystem services, as well as the possibility of spillover effects on off-site environments. Educational outreach efforts should be performed to transfer rhizosphere engineering research outcomes to farmers. Lastly, incorporating rhizosphere engineering techniques into comprehensive farming systems, in conjunction with complementary sustainable agriculture practices, will be critical for optimizing phosphorus use efficiency with reduced environmental impact. By focusing on such lines of investigation, future research in rhizosphere engineering has the potential to transform phosphorus management in agriculture.

References

- Alzate Zuluaga M.Y., Fattorini R., Cesco S. and Pii Y. (2024). Plant-microbe interactions in the rhizosphere for smarter and more sustainable crop fertilization: the case of PGPR-based biofertilizers. *Front. Microbiol.*, **15**, 1440978.
- Aono, T., Tsukagoshi S. and Yamazaki H. (2021). Modulating root exudate composition in plants for nutrient acquisition. *Plant Cell Physiol.*, **62**(2), 321–334.
- Backer, R., Rokem J.S., Ilangumaran G., Lamont J., Praslickova D., Ricci E. and Smith D.L. (2018). Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Front. Plant Sci.*, **9**, 1473.
- Bornř, M.L., Müller-Stöver D.S., and Liu F. (2018). Contrasting effects of biochar on phosphorus dynamics and bioavailability in different soil types. *Sci. Total Environ.*, **627**, 963–974.
- Chen, Q., Zhao Q., Xie B., Lu X., Guo Q., Liu G. and Liang C. (2024). Soybean (*Glycine max*) rhizosphere organic phosphorus recycling relies on acid phosphatase activity and specific phosphorus-mineralizing-related bacteria in phosphate deficient acidic soils. *J. Integ. Agricult.*, **23**(5), 1685–1702.
- Chen, Z., Wang W., Chen L., Zhang P., Liu Z., Yang X. and Mi Y. (2024). Effects of pepper–maize intercropping on the physicochemical properties, microbial communities, and metabolites of rhizosphere and bulk soils. *Environmental Microbiome*, **19**(1), 108.
- Cheng, X., Wang M., Yuan M.M., Li J. and Xiong W. (2023). Rhizosphere microbiome engineering for crop cultivation. *Front. Bioeng. Biotechnol.*, **11**, 1267442.
- Cordell, D., Drangert J.O. and White S. (2009). The story of phosphorus: Global food security and food for thought. *Glob. Environ. Change*, **19**(2), 292–305.
- Dakora, F.D. and Phillips D.A. (2002). Root exudates as mediators of mineral acquisition in low-nutrient environments. *Plant and Soil*, **245**(1), 35–47.
- Dasila, H., Sah V.K., Jaggi V., Kumar A., Tewari L., Taj G. and Sahgal M. (2023). Cold-tolerant phosphate-solubilizing *Pseudomonas* strains promote wheat growth and yield by improving soil phosphorous (P) nutrition status. *Front. Microbiol.*, **14**, 1135693.
- Drinkwater, L.E. and Snapp S.S. (2007). Nutrients in agroecosystems: Rethinking the management paradigm. *Adv. Agron.*, **92**, 163–186.
- Emami, S., Alikhani H.A., Pourbabaee A.A., Etesami H., Motasharezaheh B. and Sarmadian F. (2020). Consortium of endophyte and rhizosphere phosphate solubilizing bacteria improves phosphorous use efficiency in wheat cultivars in phosphorus deficient soils. *Rhizosphere*, **14**, 100196.
- Etesami, H., Jeong B.R. and Glick B.R. (2021). Contribution of arbuscular mycorrhizal fungi, phosphate-solubilizing bacteria and silicon to P uptake by plant. *Front. Plant Sci.*, **12**, 699618.
- FAO (2021). *The State of the World's Land and Water Resources for Food and Agriculture – Systems at Breaking Point*. Food and Agriculture Organization of the United Nations.
- Ferreira, M.J., Veríssimo A.C., Pinto D.C., Sierra-Garcia I.N., Granada C.E., Cremades J. and Cunha Â. (2024). Engineering the Rhizosphere Microbiome with Plant Growth Promoting Bacteria for Modulation of the Plant Metabolome. *Plants*, **13**(16), 2309.
- Gao, Y., Tariq A., Zeng F., Sardans J., Al Bakre D.A. and Peñuelas J. (2024). Fractions of soil phosphorus mediated by rhizospheric phoD harbouring bacteria of deep rooted desert species are determined by fine root traits. *Functional Ecology*, **38**(10), 2300–2315.
- Goodey, N.M. and Eshariah D. (n.d.). Field-Based Enhancement of Germination and Soil Phosphatase Activity In a Barren Brownfield Via Soil Mixing and Artificial Root Exudates. Available at SSRN 5262335.
- Hakim, S., Naqqash T., Nawaz M.S., Laraib I., Siddique M.J., Zia R. and Imran A. (2021). Rhizosphere engineering with plant growth-promoting microorganisms for agriculture and ecological sustainability. *Front. Sust. Food Syst.*, **5**, 617157.
- Haokip, I.C., Dwivedi B.S., Meena M.C., Datta S.P., Sharma V.K. and Saharawat Y.S. (2019). Effect of phosphorus fertilization and microbial inoculants on yield, phosphorus use-efficiency and available phosphorus in maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system. *Indian J. Agricult. Sci.*, **89**(5), 806–812.
- Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: A review. *Plant and Soil*, **237**, 173–195.
- Hopkins, B.G., Hansen N.C., Ellsworth J.W. and Jolley V.D. (2014). Phosphorus management in irrigated cropping systems. *Adv. Agron.*, **123**, 127–198.
- Khan, M.S., Zaidi A. and Ahmad E. (2014). Mechanism of phosphate solubilization and physiological functions of phosphate-solubilizing microorganisms. In : *Phosphate solubilizing microorganisms: principles and application of microphos technology* (pp. 31–62). Cham: Springer International Publishing.
- Khashi u Rahman, M., Wang X., Gao D., Zhou X. and Wu F. (2021). Root exudates increase phosphorus availability in the tomato/potato onion intercropping system. *Plant and Soil*, **464**(1), 45–62.

- Kuzyakov, Y. and Razavi B.S. (2019). Rhizosphere size and shape: temporal dynamics and spatial stationarity. *Soil Biol. Biochem.*, **135**, 343-360.
- Lambers, H., Shane M.W., Cramer M.D., Pearse S.J. and Veneklaas E.J. (2006). Root structure and functioning for efficient acquisition of phosphorus: Matching morphological and physiological traits. *Annals of Botany*, **98**(4), 693–713.
- Lehmann, J., Rillig M.C., Thies J., Masiello C.A., Hockaday W.C. and Crowley D. (2011). Biochar effects on soil biota – A review. *Soil Biol. Biochem.*, **43**(9), 1812–1836.
- Lu, K., Yang X., Shen J., Robinson B., Huang H., Liu D. and Wang H. (2014). Effect of bamboo and rice straw biochars on the bioavailability of Cd, Cu, Pb and Zn to *Sedum plumbizincicola*. *Agricult., Ecosyst. Environ.*, **191**, 124-132.
- Ma, X.F., Tudor S., Butler T., Ge Y., Xi Y., Bouton J. and Wang Z.Y. (2012). Transgenic expression of phytase and acid phosphatase genes in alfalfa (*Medicago sativa*) leads to improved phosphate uptake in natural soils. *Molecular Breeding*, **30**(1), 377-391.
- Marschner, H. (1995). Rhizosphere pH effects on phosphorus nutrition. *Genetic manipulation of crop plants to enhance integrated nutrient management in cropping systems*, **1**, 107-115.
- Meng, L., Cheng Z., Wang Y., Li S. and Clarke N. (2024). Arbuscular mycorrhizal fungal interacted with biochar and enhanced phosphate-solubilizing microorganism abundance and phosphorus uptake in maize. *Agronomy*, **14**(8), 1678.
- Negi, S., Kumar P., Kumar J., Singh A. and Dubey R.C. (2022). Indigenous nitrogen fixing microbes engineer rhizosphere and enhance nutrient availability and plant growth. In : *Rhizosphere engineering* (pp. 19-43). Academic Press.
- Pathak, H.K., Chauhan P.K., Seth C.S., Dubey G. and Upadhyay S.K. (2024). Mechanistic and future prospects in rhizospheric engineering for agricultural contaminants removal, soil health restoration, and management of climate change stress. *Sci. Total Environ.*, **927**, 172116.
- Peng, Y., Duan Y., Huo W., Zhang Z., Huang D., Xu M. and Feng G. (2022). C: P stoichiometric imbalance between soil and microorganisms drives microbial phosphorus turnover in the rhizosphere. *Biol. Fert. Soils*, **58**(4), 421-433.
- Shen, J., Yuan L., Zhang J., Li H., Bai Z., Chen X., Zhang W. and Zhang F. (2011). Phosphorus dynamics: From soil to plant. *Plant Physiology*, **156**(3), 997–1005.
- Shulse, C.N., Chovatia M., Agosto C., Wang G., Hamilton M., Deutsch S. and Blow M.J. (2019). Engineered root bacteria release plant-available phosphate from phytate. *Appl. Environ. Microbiol.*, **85**(18), e01210-19.
- Singh, U., Choudhary A.K., Varatharajan T. and Sharma S. (2022). Agricultural management practices affect the abundance of markers of phosphorus cycle in soil: Case study with pigeonpea and soybean. *J. Soil Sci. Plant Nutr.*, **22**(3), 3012-3020.
- Sui, L., Tang C., Cheng K. and Yang F. (2022). Biochar addition regulates soil phosphorus fractions and improves release of available phosphorus under freezing-thawing cycles. *Sci. Total Environ.*, **848**, 157748.
- Thioub, M., Ewusi-Mensah N., Sarkodie-Addo J. and Adjei-Gyapong T. (2019). Arbuscular mycorrhizal fungi inoculation enhances phosphorus use efficiency and soybean productivity on a Haplic Acrisol. *Soil and Tillage Res.*, **192**, 174-186.
- Tian, J., Lu X., Chen Q., Kuang X., Liang C., Deng L. and Tian J. (2022). Phosphorus fertilization affects soybean rhizosphere phosphorus dynamics and the bacterial community in karst soils. *Plant and Soil*, **475**(1), 137-152.
- Vishwakarma, K., Kumar N., Shandilya C., Mohapatra S., Bhayana S. and Varma A. (2020). Revisiting plant–microbe interactions and microbial consortia application for enhancing sustainable agriculture: A review. *Front. Microbiol.*, **11**, 560406.
- Wang, G., Jin Z., George T.S., Feng G. and Zhang L. (2023). Arbuscular mycorrhizal fungi enhance plant phosphorus uptake through stimulating hyphosphere soil microbiome functional profiles for phosphorus turnover. *New Phytologist*, **238**(6), 2578-2593.
- Wang, J., Man Y., Ruan W., Tam N.F.Y., Tao R., Yin L. and Tai Y. (2022). The effect of rhizosphere and the plant species on the degradation of sulfonamides in model constructed wetlands treating synthetic domestic wastewater. *Chemosphere*, **288**, 132487.
- Withers, P.J.A., Elser J.J., Hilton J. *et al.* (2014). Greening the global phosphorus cycle: How green chemistry can help achieve planetary P sustainability. *Green Chemistry*, **17**(4), 2087–2099.
- Yasmeen, T., Arif M.S., Shahzad S.M., Riaz M., Tufail M.A., Mubarik M.S. and Shakoar A. (2022). Abandoned agriculture soil can be recultivated by promoting biological phosphorus fertility when amended with nano-rock phosphate and suitable bacterial inoculant. *Ecotoxicol. Environ. Saf.*, **234**, 113385.
- Zhang, D., Sun Z., Feng L., Bai W., Yang N., Zhang Z. and Zhang L. (2020). Maize plant density affects yield, growth and source-sink relationship of crops in maize/peanut intercropping. *Field Crops Res.*, **257**, 107926.
- Zhang, J., Lu J., Zhu Y., Huang Q., Qin L. and Zhu B. (2022). Rhizosphere microorganisms of *Crocus sativus* as antagonists against pathogenic *Fusarium oxysporum*. *Front. Plant Sci.*, **13**, 1045147.
- Zhang, L., Chang L., Liu H., de Jesus Puy Alquiza M. and Li Y. (2025). Biochar application to soils can regulate soil phosphorus availability: A review. *Biochar*, **7**(1), 13.
- Zulfiquar, A., Azhar B., Aroosa Z., Zeenat A. and Aman S. (2021). Screening of rice varieties based on remodeling of root architecture linked to enhanced phosphorus transporters and ethylene signaling for better phosphorous acquisition under limiting conditions. *Sains Malays*, **50**, 1621-1638.