

Review Article

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Phosphate-Solubilising Bacteria: Microbial Catalysts for Sustainable Agronomy and Geobiotechnological Applications

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ABSTRACT

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Phosphate-solubilising microorganisms (PSMs), a phylogenetically heterogeneous assemblage of bacteria and fungi, occupy a singular functional niche at the intersection of microbial ecology and biotechnological innovation. Through acidification, chelation, and enzymatic hydrolysis, taxa including *Bacillus*, *Pseudomonas*, and *Rhizobium* liberate orthophosphate from recalcitrant mineral and organic pools, rendering it accessible to plant roots. This capacity sustains not only crop nutrition and yield but also fortifies plant tolerance against salinity and drought while mitigating metal mobility in polluted matrices. Yet for all their laboratory promise, PSMs have not fully crossed the threshold into mainstream agricultural practice. The impediments are human in scale: costly production pipelines, formulations that fail to preserve viability, and the ecological reality that foreign microbes often struggle to find their place in already settled soil communities. Encouragingly, the field is moving beyond proof-of-concept. Cheaper fermentation substrates, protective seed coatings, and regionally adapted isolates are narrowing the gap between potential and performance. Meanwhile, metagenomics tools are unveiling a hidden world of phosphate-solubilising diversity, and synthetic biology offers the prospect of purpose-built strains equipped for both catalytic efficiency and rhizosphere competence. As PSMs begin to find roles beyond the field of degrading organophosphate pollutants or recovering phosphorus from eutrophic waters, they increasingly embody a broader ambition: to rewire nutrient economies along more circular, less extractive lines.

Introduction

Phosphate-solubilising microorganisms (PSMs) are bacterial or fungal species that convert insoluble soil phosphorus, primarily mineral phosphates, into soluble, bioavailable forms for plant assimilation, as illustrated in Figure 1 (1). They constitute a broad category of beneficial microbes, encompassing numerous genera such as *Bacillus spp.*, *Pseudomonas spp.*, *Streptomyces*

spp., *Aspergillus spp.*, *Rhizobium spp.*, *Fusarium spp.*, *Trichoderma spp.*, *Penicillium spp.*, *Serratia spp.*, *Micrococcus spp.*, *Stenotrophomonas spp.*, *Acinetobacter spp.*, and *Agrobacterium spp.* (2). This metabolic process enhances the overall phosphorus bioavailability for plants, thereby promoting improved vegetative growth and increasing crop yields. PSMs are predominantly located in soil and the rhizosphere, where they play a critical role in nutrient cycling and the maintenance of

soil fertility (3). Phosphate-solubilising microorganisms (PSMs) also serve as versatile agents in biotechnology. In industrial contexts, such as pharmaceutical manufacturing and food processing, specific PSM strains are harnessed for the production of antibiotics, vitamins, and various other bioactive compounds (4). Furthermore, PSMs hold significant potential for advancing novel and efficient bioprocesses aimed at the sustainable production of biofuels and other bio-based industrial products (5). The most prominent applications of Phosphate-Solubilising Microorganisms (PSMs) are in agriculture and environmental engineering. Leveraging their beneficial metabolic functions, PSMs are utilised as biofertilizers to enhance soil fertility and promote plant growth, while also improving crop resilience against abiotic stresses such as salinity (6), malnourishment (7,8), etc. Consequently, their application contributes to increased crop yields (9). PSMs are also employed in bioremediation, either independently or in conjunction with plants, to detoxify contaminated environments by mobilising and sequestering pollutants such as heavy metals from soil and water (10, 11).

Phosphate availability in soil

Phosphorus (P) is an essential macronutrient found in soil at concentrations of 400–1200 mg·kg⁻¹ (12). Its biogeochemical cycle is sedimentary, lacking a gaseous atmospheric phase. Microorganisms drive terrestrial P cycling via redox reactions spanning oxidation states from -3 (phosphine) to +5 (phosphate). However, the genetic and biochemical mechanisms governing these transformations remain poorly understood (13). Soluble phosphorus (P) in soil solution is typically below 1 ppm (~10 μM H₂PO₄⁻), with orthophosphate ions (HPO₄²⁻ and H₂PO₄⁻) being the primary plant-available forms (14). Geological deposits—chiefly apatite, hydroxyapatite, and oxyapatite constitute the largest P reserves, though their inherent insolubility limits immediate bioavailability. India alone possesses an estimated 40 million tons of phosphatic rock, a potential low-cost fertiliser source (15). Under suitable conditions, these minerals undergo solubilisation. In ferrallitic soils, P is further occluded within hydrated Fe, Al, and Mn oxides, enhancing fixation capacity. Although agricultural soils often accumulate substantial total P from long-term fertilisation, most applied inorganic P is rapidly immobilised into insoluble or poorly labile forms (16). P retention is pH-dependent: in acidic soils, P is fixed by Al- and Fe-oxides; in alkaline soils, it precipitates as calcium phosphates. These processes substantially reduce

the efficiency of soluble fertilisers like superphosphate. Organic P constitutes 30–50% of total soil P, ranging from 5% to 95% depending on soil type. The dominant fraction is inositol phosphate (phytate), accounting for up to 50% of organic P (17). Other forms include phosphomonoesters, phosphodiester (e.g., phospholipids, nucleic acids), and phosphoesters. Nucleic acid derivatives represent only ~1% of identifiable organic P, while phospholipid P typically ranges from 1–5 ppm, occasionally up to 34 ppm. Most organic P compounds are high-molecular-weight polymers requiring enzymatic hydrolysis into soluble inorganic phosphate (Pi, HPO₄²⁻, H₂PO₄⁻) or low-molecular-weight organic phosphates for cellular uptake. Additionally, synthetic organophosphates used as pesticides, detergents, antibiotics, and flame retardants are persistent environmental contaminants due to stable C–P bonds. Emerging evidence indicates that certain microorganisms can liberate P from these xenobiotic compounds, expanding the known functional scope of the microbial P cycle (18).

Phosphate-solubilising bacteria

Several reports have examined the ability of different bacterial species to solubilise insoluble inorganic phosphate compounds, such as tricalcium phosphate, dicalcium phosphate, hydroxyapatite, and rock phosphate (19). Among the bacterial genera with this capacity are *Pseudomonas*, *Bacillus*, *Rhizobium*, *Burkholderia*, *Achromobacter*, *Agrobacterium*, *Micrococcus*, *Aerobacter*, *Flavobacterium* and *Erwinia*.

Phosphate-solubilising bacteria (PSB) are abundant in both bulk soil and plant rhizospheres, with notably higher populations in the rhizosphere. Both aerobic and facultatively anaerobic strains exist; aerobes predominate in submerged soils (20). Plate screening methods using insoluble mineral phosphates (e. g., tricalcium phosphate, hydroxyapatite) as the sole P source remain a reliable tool for isolating and preliminarily characterising PSB, despite occasional inconsistencies between halo formation and liquid culture performance (21). An improved method incorporating bromophenol blue enables visualisation of organic acid-mediated pH drops via yellow halos, yielding more reproducible and correlative results (Gupta *et al.*, 1994). In vitro solubilisation is commonly quantified by measuring P released into the culture broth, subtracting residual P from the initial substrate P. However, this approach overlooks P consumed for cellular metabolism (23). P

accumulation kinetics vary among strains: Babenko *et al.*, classified PSB into four types based on solubilisation dynamics, ranging from linear P accumulation to oscillatory patterns with multiple peaks and troughs. The latter has been corroborated elsewhere (24). Oscillatory behaviour may arise from P pre-precipitation with organic metabolites, transient formation and re-utilisation of organo-P complexes, or differential rates of P solubilisation versus uptake (23). A combination of these mechanisms is plausible. Consequently, single-point P measurements may misrepresent true solubilisation capacity; kinetic profiling offers a more robust assessment. Table 1 summarizes the solubilisation ability of different insoluble P substrates by several bacterial species. Although no accurate quantitative comparison can be made from experiments from different sources, the data suggest that *Rhizobium*, *Pseudomonas* and *Bacillus* species are among the most powerful solubilisers, while tricalcium phosphate and hydroxyapatite seem to be more degradable substrates than rock phosphate.

Harnessing Phosphate-Solubilising Microbes for Agriculture and Bioremediation

Phosphate-solubilising microorganisms (PSMs) present a significant biotechnological opportunity for sustainable resource management. Amidst growing global population pressures and the consequent strain on finite phosphate reserves, PSMs offer a strategic pathway to enhance soil fertility and reduce dependency on synthetic fertilisers (29,30). Phosphate-solubilising microorganisms (PSMs) represent an emerging biotechnology with promising applications in agriculture and environmental engineering. However, the field remains predominantly in the experimental and laboratory phases, with commercialisation yet to be realised. While foundational research validates their potential for plant growth promotion, soil enhancement, and contaminant detoxification, significant translational development is required for widespread practical deployment (10,31,32).

Agriculture Purpose

By enhancing the solubility of fixed soil phosphorus, phosphate-solubilising microorganisms (PSMs) directly influence plant metabolic processes. This elevated phosphorus bioavailability serves as a key regulatory signal, inducing systemic changes in growth patterns and primary metabolic pathways within the plant (23). This metabolic reprogramming translates into key agronomic

benefits, most notably increased photosynthetic efficiency, accelerated root biomass development, and the upregulation of defence pathways that confer tolerance to both drought conditions and disease (33,34). The provision of soluble phosphorus by PSMs serves a dual purpose: nutritional and signalling. This phosphorus surge triggers specific signalling pathways that upregulate stress-responsive gene networks in plants. Consequently, critical physiological functions are enhanced, including osmoregulation (via aquaporin genes), oxidative stress mitigation (through antioxidant enzymes), and thermal protection (via heat shock proteins). This coordinated genetic response underpins the observed improvement in tolerance to diverse abiotic stressors such as drought, salinity, and heavy metals (35). In addition, PSMs can modulate plant physiology through the synthesis or stimulation of key phytohormones, including auxins, cytokinins, and gibberellins. As outlined in Figure 1, this hormonal regulation promotes root development, cell division, and overall growth, while simultaneously enhancing the plant's systemic tolerance to various environmental stresses.

Environmental engineering purpose

Phosphate-solubilising microorganisms (PSMs) contribute to the remediation of heavy metal-contaminated soils through an indirect immobilisation mechanism, as illustrated in Figure 1. The phosphate ions released during microbial solubilisation compete with and precipitate bioavailable metal ions, forming stable, less soluble complexes. This process effectively reduces heavy metal uptake by plants and lowers their concentration in the soil solution, whether PSMs act independently or in combination with other amendments or microbial species (32,36,37). In addition to phosphate-mediated immobilisation, certain PSMs directly assist in heavy metal remediation through the secretion of low-molecular-weight organic acids, such as citric acid.

As indicated in Figure 1, these acids act as potent chelating agents, binding to heavy metal ions in the soil and forming stable complexes that significantly reduce their bioavailability and subsequent uptake by plants.

An indirect facilitation strategy for heavy metal remediation involves PSMs promoting phytoremediation (see Figure 1). In this approach, PSMs improve the phosphorus nutrition of specialised hyperaccumulator or metal-tolerant plants, boosting their biomass and health.

This enhanced growth, in turn, increases the plant's capacity to extract and accumulate heavy metals from contaminated soil, making the overall phytoremediation process more effective. Despite the compelling functional potential of PSMs, key challenges must be addressed to enable widespread application. Further research is required to elucidate their complex interactions with plants and soil ecosystems fully. Concurrently, significant translational work is needed to overcome barriers in cost-effective mass production, stable formulation, and scalable delivery methods for use in agriculture and environmental engineering. The multifunctional applications of phosphate-solubilising microorganisms (PSMs) in agriculture and environmental engineering are summarised in Table 1.

Challenges and Solutions in the Commercialisation of Phosphate-Solubilising Microorganisms

The practical deployment and commercialisation of phosphate-solubilising microorganisms (PSMs) in agriculture and environmental engineering face several significant challenges:

- **Lack of Standardisation:** The absence of standardised protocols for production, formulation, and application leads to variable field efficacy and inconsistent performance as bio-fertilisers or soil remediation agents.
- **Environmental Sensitivity & Persistence:** PSM survival and functionality are highly dependent on soil conditions (e.g., pH, salinity, and heavy metal content). Furthermore, introduced inoculants often exhibit poor long-term persistence in the soil, limiting their sustained impact.
- **Microbial Competition:** In native soil ecosystems, introduced PSMs encounter intense competition from indigenous microbial communities for nutrients and ecological niches, which can impede successful colonisation and establishment.
- **Economic Viability:** The costs associated with large-scale production, formulation, and application of PSMs remain high, posing a primary economic barrier to widespread adoption.

Among these factors, high production costs and intense competition from resident soil microbes are currently the most critical obstacles to successful commercialisation. These challenges underscore the need for targeted research to optimise PSM formulations, enhance their

ecological competence, and develop cost-effective application strategies to unlock their full potential for sustainable soil management.

To enhance the economic feasibility of phosphate-solubilising microorganisms (PSMs), several cost-reduction strategies can be pursued:

Scalable, Low-Cost Production: Implementing efficient mass production techniques, such as optimised fermentation processes using inexpensive substrates, is essential for reducing the per-unit cost of PSMs at a commercial scale.

Efficient Application Formulations: Developing and deploying cost-effective delivery systems, including granular formulations (38), liquid inoculants (39), or seed coatings, can minimise application costs and improve field efficacy.

Strategic Strain Selection: Prioritising the use of native, widely distributed, or easily colourable PSM strains with high environmental adaptability can lower isolation, maintenance, and production expenses (40).

Utilisation of Natural Phosphate Sources: Integrating PSMs with low-cost, natural phosphate sources (e.g., rock phosphate or guano) can reduce dependency on expensive soluble fertilisers, enhancing the overall value proposition of PSM-based strategies.

Adoption of Integrated Nutrient Management (INM): Combining PSMs within broader INM frameworks such as cover cropping, composting, and intercropping improves system-wide nutrient use efficiency and reduces reliance on external fertiliser inputs, thereby increasing the cost-effectiveness of PSM application.

Implementing these strategies collectively can address key economic barriers and facilitate the broader adoption of PSMs in sustainable agriculture.

To mitigate competition with indigenous soil microorganisms, including plant pathogens, decomposers, and predators and ensure the successful establishment of phosphate-solubilising microorganisms (PSMs), the following application parameters should be optimised:

Table.1 Total P accumulation in cultures of different bacterial species grown on insoluble mineral phosphate substrates (mg L⁻¹)

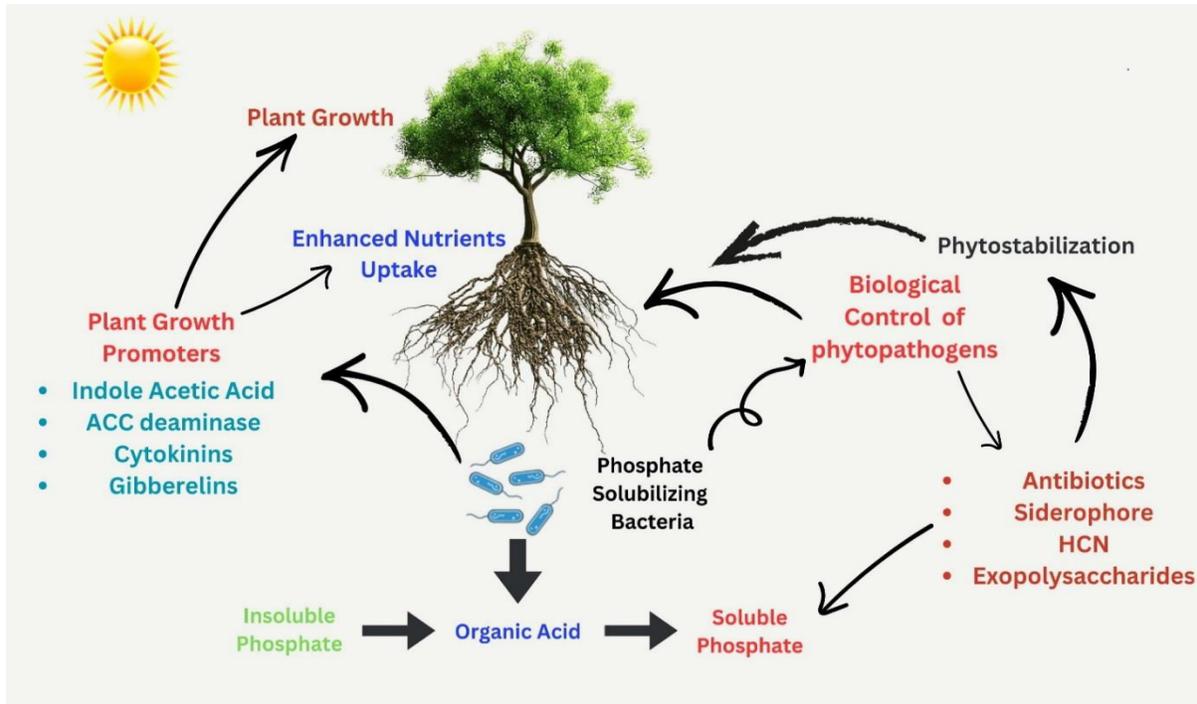
Bacterial Strain	Substrate			References
	Ca ₃ (PO ₄) ₂	Hydroxy-apatite	Rock phosphate	
<i>Pseudomonas sp.</i>	52	ND	ND	(21)
<i>Pseudomonas striata</i>	156	143	22	(25)
<i>Bacillus polymyxa</i>	116	87	17	
<i>Bacillus megaterium</i>	82	31	16	
<i>Rhizobium sp.</i>	ND	300	ND	(26)
<i>Rhizobium meliloti</i>	ND	165	ND	(26)
<i>Rhizobium leguminosarum</i>	ND	356	ND	
<i>Rhizobium loti</i>	ND	27	ND	
<i>Bacillus amyloliquefaciens</i>	395	ND	ND	(27)
<i>Burkholderia cepacia</i>	35	ND	ND	(28)
<i>Bacillus pulvifaciens</i>	54	65	13	(25)
<i>Bacillus circulans</i>	11	17	6	
<i>Citrobacter freundii</i>	16	7	5	

ND indicates not determined.

Table.2 Applications and Functional Benefits of Phosphate-Solubilizing Microorganisms in Agriculture and Environmental Engineering

Agriculture	Environmental Engineering
Enhance soil nutrient status	Extract and recycle phosphorus from wastewater
Stimulate plant development	Upgrade overall water quality
Improve efficiency of nutrient absorption	Control and prevent eutrophication
Strengthen plant defence mechanisms	Support bioremediation of polluted soils
Minimize dependence on chemical fertilizers	Restore soil quality in mining areas
Increase agricultural productivity	Assist vegetation growth on degraded lands
Improve plant tolerance to environmental stress	Promote microbial diversity in ecosystems
Raise levels of soil organic content	Reduce negative effects of agricultural runoff
Develop better soil aggregation and stability	Enhance carbon storage in soils
Control and prevent soil erosion	Encourage sustainable land-use practices

Figure.1 Phosphorus-solubilising microorganisms enhance plant growth and soil health by converting insoluble phosphorus into a form plants can absorb, while also contributing to the remediation of contaminated soils.



Soil Preparation: Before inoculation, soil conditions should be optimised to favour PSM survival. This includes amending soil with organic matter, adjusting pH to a suitable range, and mitigating excessive salinity to create a more hospitable microenvironment.

Inoculum Preparation: Inocula should be formulated to enhance stress tolerance and persistence. Strategies include selecting PSMs with inherent resistance to local abiotic stressors (e.g., heavy metals, salinity) and employing protective formulations that improve microbial shelf-life and soil survivability (Johri *et al.*, 1999).

Timing of Application: Inoculation timing can be strategically aligned with periods of reduced indigenous microbial activity, such as early in the growing season, to minimise initial competitive pressure and improve PSM colonisation.

Competitive Strain Selection: PSMs should be screened for competitive traits, such as rapid root colonisation, effective resource utilisation, and/or the production of antagonistic metabolites (e.g., antibiotics,

siderophores) that can suppress competing microorganisms.

Microbial Community Management: The soil microbiome can be preconditioned to support PSM establishment through amendments like compost or mulch, which modify microbial community structure, or via co-inoculation with compatible helper microbes or biostimulants that enhance PSM fitness.

Collectively, optimising these factors increases the likelihood of successful PSM establishment, persistence, and function in complex soil ecosystems, thereby improving the reliability of their application.

Advancing PSM Science: Key Research Frontiers

A key frontier in PSM research lies in **microbial ecology**, focusing on the complex interactions between phosphate-solubilising microorganisms and the broader soil microbiome.

This includes elucidating competitive and cooperative dynamics to clarify their role in maintaining soil health

and nutrient cycling. Concurrent research aims to develop ecological strategies that enhance PSM survival and functional persistence across diverse soil environments (41).

Metagenomics is employed to analyse the diversity and functional potential of PSMs in complex soil ecosystems, facilitating the discovery of novel strains with superior phosphate-solubilising capabilities and plant growth-promoting traits.

Biostimulants, comprising PSMs and other beneficial microbes, are investigated for their role in enhancing plant vigour, productivity, and resilience to environmental stressors (42).

Synthetic Biology enables the targeted enhancement of PSM functionality, including the engineering of strains with improved phosphate solubilisation efficiency. Approaches range from the application of CRISPR-Cas9 gene editing to the *de novo* design of synthetic microbial consortia (6).

Soil Remediation research focuses on deploying PSMs for the detoxification of contaminated environments, particularly through the immobilisation or removal of heavy metals (43). This includes optimising application methods and elucidating the underlying biochemical mechanisms of contaminant mitigation.

In conclusion, Phosphate-solubilising microorganisms constitute a significant biotechnological resource positioned at the nexus of sustainable crop production and environmental biotechnology. Evidence synthesised in this review confirms that PSMs notably including taxa such as *Pseudomonas*, *Bacillus*, and *Rhizobium* exhibit well documented mechanisms for mobilising insoluble soil phosphorus fractions through organic acid-mediated dissolution and enzymatic depolymerisation. This functional attribute supports multiple agronomic and environmental outcomes: increased crop biomass, enhanced physiological tolerance to salinity and water deficit, and reduced bioavailability of toxic metallic species in contaminated substrates. Notwithstanding extensive laboratory validation and demonstrable proof-of-concept, large-scale commercial implementation of PSM-based technologies remains limited. Translational bottlenecks are principally attributable to two interrelated factors: the economic burden of industrial-scale cultivation and formulation, and the poor rhizosphere competence of allochthonous strains when

introduced into established soil microbiomes. Mitigation of these constraints necessitates integrated approaches encompassing bioprocess optimisation—specifically, the use of cost-effective growth substrates and fermentation regimes—alongside the development of application technologies such as granular carriers, seed coatings, and co-formulants that prolong viability and delivery efficiency. Concurrently, ecological fitness must be augmented through selection of edaphic-adapted isolates, formulation chemistries that confer desiccation and predation resistance, and temporally strategic inoculation schedules. Future investigative priorities should centre on the deployment of high-resolution meta-omic platforms to resolve cryptic PSM diversity and identify genetic determinants of environmental persistence and catalytic efficiency. Synthetic biology methodologies, including targeted genome editing and pathway refactoring, present viable routes for the construction of strains with augmented phosphate mineralisation capacity and rhizosphere colonisation proficiency. Elucidation of multitrophic interactions among PSMs, resident microbiota, and plant hosts will be essential to decipher the community-level mechanisms governing inoculant establishment and functional durability. Additionally, emerging applications in xenobiotic organophosphate degradation and phosphate recovery from eutrophic water systems warrant systematic exploration. In summary, phosphate-solubilising bacteria exemplify the convergence of microbial metabolic diversity and applied biotechnological design. Continued interdisciplinary investment—bridging molecular microbiology, process engineering, and soil ecology will be critical to advance PSMs beyond proof-of-concept toward operational deployment. Realisation of this translational trajectory offers a viable mechanism to curtail reliance on chemical phosphate fertilisers, rehabilitate anthropogenically degraded landscapes, and reinforce the sustainability intensification of global agricultural systems.

Author Contributions

Devanshi Patel: Investigation, formal analysis, writing—original draft. Nilofar Bhatti: Validation, methodology, writing—reviewing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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