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Dual Role of P-Solubilizing Bacteria: Nutrient Mobilization and Plant Protection

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Phosphorus (P) is one of the most essential macronutrients for plant growth, ranking just after nitrogen in importance. Phosphorus, a fundamental element in DNA, cell membranes, and energy-transfer molecules, plays a vital role in plant life by supporting cell division, root and stem strength, flower and seed development, crop maturity, and overall quality, while also integrating closely with nitrogen and carbon metabolism, as well as photosynthesis, to drive essential growth and energy processes. Yet, despite its abundance in soils, making up about 0.05% by weight, only a tiny fraction (around 0.1%) is actually available for plant uptake, as most of it exists in forms that plants can't absorb. This poor availability, caused by phosphorus becoming quickly locked up in the soil, makes it a major limiting factor in crop productivity. As a result, ensuring plants get enough accessible phosphorus remains a key challenge in modern agriculture.

To tackle phosphorus deficiency in soils, modern agriculture has long relied on the heavy use of chemical phosphate fertilizers. These fertilizers initially flood the soil with soluble phosphate, yet plants manage to absorb only about 20% of what's applied. The rest quickly binds to soil particles, becoming unavailable to crops. Over time, the excessive and repeated use of these fertilizers has sparked serious concerns, degrading soil health, disrupting microbial communities, and polluting ecosystems. In many developing regions, the widespread and unchecked use of agrochemicals to boost yields has compromised soil fertility, biodiversity, groundwater quality, and food safety, posing a direct threat to long-term agricultural sustainability and planetary health. Furthermore, plants face a combination of challenges, from abiotic and biotic stresses to hormonal imbalances and nutrient deficiencies, all of which hamper growth and yield. Nature, however, holds a sustainable solution to this challenge. Recent advances highlight the potential of phosphorus-solubilizing microorganisms (PSMs) beneficial microbes that unlock soil-bound phosphorus, offering a sustainable and eco-friendly alternative to chemical fertilizers.

Phosphorus-Solubilizing Bacteria: Nature's Multifunctional Soil Engineers

Phosphorus-solubilizing microorganisms (PSMs) have been extensively explored as potential biofertilizers due to their natural ability to support plant nutrition and growth. These beneficial microbes, often found in phosphorus-rich zones, can be isolated and applied to crops to boost the availability of phosphorus, a nutrient that is often locked in insoluble forms in the soil. Beyond solubilizing phosphorus, PSMs enhance soil fertility, enrich phosphorus availability, and improve nutrient uptake. Among PSMs, Phosphorus-solubilizing bacteria (PSB) have emerged as particularly effective agents due to their remarkable efficiency in mobilizing soil-bound phosphorus. Many PSBs also produce phytohormones like IAA, gibberellins, and cytokinins, and synthesize ACC deaminase, which helps plants cope with stress. They generate siderophores that enhance iron availability and suppress pathogenic microbes (Fig. 1) in the rhizosphere (Misra and Chauhan, 2020).

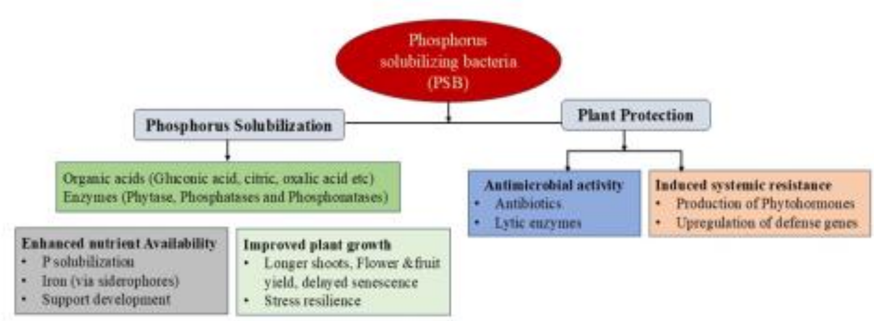

Fig. 1: Role of Phosphorus solubilizing bacteria

A diverse group of soil microbes including Pseudomonas, Bacillus, Azotobacter, Agrobacterium, Burkholderia, Rhizobium, Bradyrhizobium, Enterobacter, Erwinia, Achromobacter, Flavobacterium, Micrococcus and Aerobacter have demonstrated the ability to break down insoluble phosphate compounds like dicalcium phosphate, tricalcium phosphate, and hydroxyapatite. These microorganisms, collectively known as phosphate-solubilizing bacteria (PSB), are increasingly valued in agro-ecological systems for their capacity to enhance phosphorus availability, support plant growth, and sustain soil fertility (de Boer et al., 2019).

Pseudomonas species, in particular, are notable for their adaptability to diverse environments and exceptional metabolic versatility. These PSBs are capable of solubilizing both inorganic and organic forms of phosphorus and often exhibit strong antagonistic activity against soil-borne plant pathogens. This multifunctional nature makes them excellent candidates for eco-friendly, multi-purpose biofertilizers.

Mechanism of Phosphorus Solubilization by Soil Bacteria

Phosphorus solubilizing bacteria (PSB) help plants access phosphorus by breaking down both inorganic and organic phosphate compounds. Their primary strategy involves producing organic acids such as gluconic, citric, oxalic, lactic, and acetic acids. These acids lower soil pH and chelate metal ions that typically bind phosphorus, thereby releasing it into a form accessible to plants. Gluconic and 2-ketogluconic acids are particularly important and are commonly produced by bacteria such as Pseudomonas putida, Burkholderia cepacia, Rhizobium leguminosarum, and Bacillus firmus. This acid production is driven by enzymes like glucose dehydrogenase (GDH), which requires the cofactor PQQ (pyrroloquinoline quinone), and gluconate dehydrogenase (GAD). Genes such as pqqABCDEF, which regulate PQQ biosynthesis, are critical for this function; their disruption significantly reduces phosphate solubilization capacity.

In addition to acid production, some PSBs release hydrogen ions (H^+) in exchange for cation uptake, aiding phosphate release through ion exchange rather than pH alteration. When targeting organic phosphorus compounds, bacteria secrete specific enzymes like:

Non-specific acid phosphatases (NSAPs) – including acid and alkaline phosphomonoesterases that hydrolyze phosphoesters and phosphoanhydrides. Inoculation with PSB strains like Klebsiella RC3 and RCJ4, Serratia RCJ6, Stenotrophomonas RC5, and Enterobacter RJAL6 has demonstrated strong acid and alkaline phosphatase activity under phosphorus-deficient and aluminum-toxic conditions (Barra et al., 2018).

Phytases – which break down phytate to release inorganic phosphate (Pi). Phytases are especially significant for releasing phosphorus from phytate, one of the major forms of organic phosphorus in soils. Microorganisms such as Citrobacter, Pseudomonas, and Rhizobium are among the most active phytase producers (Kumar et al., 2017).

Phosphonatases and C–P lyases – which degrade complex organophosphonates.

Notable bacterial groups contributing to these processes include Bacillus, Arthrobacter, and Rhodococcus (Gram-positive), and Pseudomonas, Rhizobium, Citrobacter, and Delftia (Gram-negative). These mechanisms—acid secretion, metal ion chelation, and ion exchange—work synergistically to convert insoluble phosphorus into bioavailable forms. Among these, Pseudomonas fluorescens stands out for its plant growth-promoting potential, as demonstrated in tomato cultivation, where its application led to enhanced shoot length, increased flowering, higher fruit set, and greater total yield.

Biocontrol activity

Although the primary agricultural application of phosphorus-solubilizing bacteria (PSB) lies in enhancing phosphorus availability, recent research highlights their broader ecological roles in the soil microbiome. PSB significantly influence rhizospheric microbial diversity and community composition by interacting with indigenous microorganisms. Such interactions often result in the enrichment of beneficial microbial taxa, thereby creating a favorable microecological niche for plant development. Importantly, PSB are increasingly recognized for their antagonistic potential against phytopathogens, a trait common among plant growth-promoting rhizobacteria (PGPR). Certain PSB strains exhibit biocontrol activity by producing antimicrobial compounds or competing for niche and resources, thereby reducing disease incidence.

Pseudomonas putida MTCC 5279 has shown remarkable ability to support plant growth under combined salt stress and phosphorus deficiency in Arabidopsis thaliana. This strain enhanced levels of IAA and ABA, increased phosphatase activity, and upregulated several stress-related genes—including those involved in DNA repair (At3g32920), jasmonate response (At2g46370), and NAC-domain transcription (At5g39610), resulting in delayed leaf senescence and improved stress resilience (Sonal and Suchi, 2020).

Recent work by Bouizgarne et al. (2023) has also highlighted the promising potential of Pseudomonas strain Bg32c as a biofertilizer and biopesticide. This strain not only improved growth and yield in cherry tomatoes but also suppressed Clavibacter michiganensis subsp. michiganensis, a serious pathogen in greenhouse-grown tomatoes.

For instance, Serratia marcescens Pt-3, isolated from tea rhizosphere, has demonstrated antifungal activity against a broad spectrum of seven phytopathogenic fungi. Similarly, Burkholderia sp. strain N3 has shown the ability to suppress bacterial diseases, significantly lowering pathogen-induced plant damage.

Limitations

Various phosphorus-solubilizing bacteria play a significant role in plant growth and phosphorus mobilization, being well-known for their multifaceted contributions to plant growth promotion and biocontrol. They produce phytohormones, antimicrobial compounds, lytic enzymes, and siderophores, and can induce systemic resistance in plants. However, their effectiveness in real field conditions often falls short of the promising results observed in laboratory studies. One major limitation is their reduced survival and colonization in natural soils, where they must compete with a well-established native microbial community. To overcome this, careful formulation of the selected strain is crucial. Bioformulations, whether in liquid, powder, granular, or capsule forms, can significantly enhance the microbial shelf life, improve stress tolerance, and support successful field establishment, ultimately ensuring the desired plant protection and growth benefits.

Conclusion

Phosphorus-solubilizing bacteria (PSB) play a pivotal role in sustainable agriculture by improving phosphorus availability and contributing to disease resistance through their antimicrobial properties and influence on rhizospheric microbial communities. Their dual role as biofertilizers and biopesticides highlights their value in enhancing plant productivity and resilience. However, the transition from laboratory efficacy to consistent field performance remains a challenge due to their reduced survival and competitiveness in native soil ecosystems. This underscores the need for optimized bioformulations—such as liquid, powder, granular, or encapsulated forms—that can extend shelf life, protect microbial viability, and support successful colonization under diverse environmental conditions. With proper formulation and field validation, PSB strains such as Pseudomonas, Bacillus, Rhizobium, Erwinia, Agrobacterium, Micrococcus, Achromobacter, and Flavobacterium can serve as eco-friendly alternatives to synthetic agrochemicals, offering a sustainable pathway to improved crop health and soil fertility.

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