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Phosphorus Dynamics And The Role Of Phosphate-Solubilizing Bacteria In Enhancing Productivity And Nutrient Use Efficiency Of Groundnut (Arachis Hypogaea L.)

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Abstract: Phosphorus (P) is a critical macronutrient limiting groundnut productivity due to its low availability and high fixation in soils. Groundnut (Arachis hypogaea L.), being a leguminous crop, requires adequate phosphorus for root development, nodulation, nitrogen fixation, and pod formation. Phosphorus deficiency can reduce yield by 20–30% in tropical soils. Phosphate-solubilizing bacteria (PSB) enhance phosphorus availability by converting insoluble phosphates into plant-accessible forms through organic acid production, enzymatic activity, proton extrusion, and chelation mechanisms (Etesami et al., 2023; García-Berumen et al., 2024). Integration of PSB with phosphorus fertilization improves phosphorus use efficiency by 20–40%, enhances crop productivity, and reduces dependence on chemical fertilizers (Yang et al., 2025). Recent advances in molecular and microbial approaches have further enhanced the efficiency of PSB under diverse soil conditions. This review synthesizes recent advances in phosphorus dynamics, PSB-mediated mechanisms, and their role in improving growth, yield, and soil health in groundnut-based systems.

Index Terms - Groundnut, Phosphorus, PSB, Nutrient use efficiency, Biofertilizer, Sustainable agriculture

I. INTRODUCTION

Groundnut (Arachis hypogaea L.) is a major oilseed crop cultivated across diverse agro-climatic conditions in India. Its productivity is often constrained by nutrient deficiencies, particularly phosphorus, which plays a significant role in plant metabolism and energy transfer (Vance et al., 2019). Indian soils, especially in semi-arid regions, are characterized by low phosphorus availability due to fixation processes involving calcium, iron, and aluminium compounds (Sharma et al., 2020).

Globally, more than 40% of cultivated soils are deficient in available phosphorus, posing a serious constraint to crop productivity (FAO, 2024). Improving phosphorus use efficiency is therefore essential for sustainable agricultural production (Zhang et al., 2023).

The use of biofertilizers such as phosphate-solubilizing bacteria (PSB) has emerged as an eco-friendly strategy to enhance phosphorus availability and reduce dependence on chemical fertilizers (Alotaibi et al., 2024). PSB improve nutrient cycling and plant growth through multiple biochemical and molecular mechanisms (Bakhshandeh et al., 2023). Therefore, integrating microbial approaches such as PSB with conventional fertilization strategies is essential for sustainable phosphorus management in groundnut cultivation. However, the variability in PSB efficiency under different soil conditions remains a major challenge, necessitating further research. Despite these advancements, a comprehensive understanding of the interaction between soil phosphorus dynamics and PSB efficiency under varying agro-ecological conditions is still lacking, highlighting the need for integrated and site-specific nutrient management strategies.

II. ROLE OF PHOSPHORUS IN GROUNDNUT

Phosphorus is one of the most essential macronutrients required for the growth and development of groundnut. It plays a fundamental role in several physiological and biochemical processes, including energy transfer, photosynthesis, signal transduction, and macromolecule biosynthesis (Vance et al., 2019; Zhang et al., 2023). Being a leguminous crop, groundnut has a high demand for phosphorus, particularly during early growth stages and reproductive development (Singh and Reddy, 2021). Adequate phosphorus supply ensures proper root establishment, efficient nodulation, and improved yield performance (Sharma et al., 2024).

2.1 Root Growth and Development

Phosphorus plays a vital role in the development of a robust root system in groundnut. It promotes root elongation, lateral root formation, and root hair proliferation, thereby increasing the effective root surface area (Vance et al., 2019). A well-developed root system enhances the plant's ability to explore a larger volume of soil for water and nutrients (Zhang et al., 2023). This is particularly important under rainfed and nutrient-deficient conditions, where efficient nutrient acquisition determines crop productivity (Sharma et al., 2020). Phosphorus deficiency restricts root growth, resulting in poor nutrient uptake and reduced plant vigour (Singh and Reddy, 2021).

2.2 Nodulation and Nitrogen Fixation

Groundnut forms a symbiotic association with nitrogen-fixing bacteria (Rhizobium spp.), enabling biological nitrogen fixation (Singh and Reddy, 2021). Phosphorus is a critical element in this process, as it provides the energy required for nodule formation and functioning (Vance et al., 2019). Adequate phosphorus availability enhances both the number and activity of nodules by supporting ATP synthesis and metabolic processes within nodules (Sharma et al., 2024). This leads to increased nitrogen fixation, improved plant nutrition, and reduced dependence on external nitrogen inputs (Alotaibi et al., 2024). Under phosphorus-deficient conditions, nodulation is significantly impaired, resulting in poor nitrogen fixation and reduced crop productivity (Singh and Reddy, 2021).

2.3 Flowering and Pod Formation

Phosphorus plays a crucial role in reproductive development, particularly in flowering, peg formation, and pod development in groundnut (Singh and Reddy, 2021). It facilitates early flowering and improves peg penetration into the soil, which is essential for pod formation (Sharma et al., 2024). Adequate phosphorus ensures proper development of reproductive organs and enhances the conversion of flowers into mature pods (Zhang et al., 2023). Deficiency of phosphorus often results in delayed flowering, poor peg formation, and reduced pod set, ultimately lowering yield potential (Singh and Reddy, 2021).

2.4 Seed Quality

Phosphorus significantly influences seed quality parameters such as oil content, protein concentration, and seed size (Zhang et al., 2023). It is involved in energy metabolism and the synthesis of nucleic acids and proteins, which are essential for seed development (Vance et al., 2019). Adequate phosphorus nutrition improves kernel filling, resulting in better seed weight and quality (Sharma et al., 2024). In oilseed crops such as groundnut, phosphorus also contributes to increased oil accumulation, thereby enhancing the economic value of the produce (Singh and Reddy, 2021).

III. SOIL PHOSPHORUS DYNAMICS

Soil phosphorus exists in various chemical forms; however, only a small fraction is available for plant uptake (Sharma et al., 2020). This limited availability is primarily due to fixation reactions with calcium in alkaline soils and with iron and aluminium in acidic soils, forming insoluble compounds (Bakhshandeh et al., 2023). As a result, phosphorus use efficiency in agricultural systems is often below 20% (Vance et al., 2019). Furthermore, phosphorus mobility in soil is very low, restricting its diffusion toward plant roots (Li et al., 2023). Therefore, improving phosphorus availability through biological approaches such as microbial interventions is essential (Etesami et al., 2023).

IV. MECHANISMS OF PHOSPHATE-SOLUBILIZING BACTERIA (PSB)

Phosphate-solubilizing bacteria (PSB) enhance phosphorus availability in soil through a range of biochemical and molecular mechanisms that convert insoluble phosphorus into plant-available forms (García-Berumen et al., 2024; Etesami et al., 2023). These mechanisms act synergistically in the rhizosphere to enhance phosphorus availability, influenced by microbial strains, soil properties, and root–microbe interactions.

4.1 Organic Acid Production

One of the primary mechanisms employed by PSB is the production of low-molecular-weight organic acids such as gluconic, citric, oxalic, and lactic acids (Etesami et al., 2023). These organic acids reduce soil pH in the rhizosphere and dissolve mineral phosphates by releasing phosphorus from insoluble complexes (Bakhshandeh et al., 2023). This acidification process significantly enhances phosphorus solubility and availability to plants (Li et al., 2023).

4.2 Enzymatic Activity

PSB produce enzymes such as phosphatases and phytases that mineralize organic phosphorus compounds into inorganic forms (García-Berumen et al., 2024). These enzymes increase the pool of available phosphorus, particularly in soils rich in organic matter (Etesami et al., 2023).

4.3 Proton Extrusion

Phosphate-solubilizing bacteria release hydrogen ions (H^+) into the soil, leading to a decrease in pH and enhanced dissolution of phosphate minerals (Sharma et al., 2020). This mechanism further contributes to increasing phosphorus availability in the rhizosphere (Bakhshandeh et al., 2023).

4.4 Chelation

Organic acids produced by PSB chelate metal ions such as calcium, iron, and aluminium that are bound to phosphate (Zaidi et al., 2021). This process releases phosphorus from insoluble complexes and makes it accessible to plants (Li et al., 2023).

4.5 Molecular Mechanisms

At the molecular level, phosphate solubilization is regulated by genes such as the pqq gene cluster, which controls gluconic acid production (Zhu et al., 2025). This gene-mediated mechanism enhances the efficiency of PSB in mobilizing phosphorus under different soil conditions (García-Berumen et al., 2024).

V. ROLE OF PSB IN GROUNDNUT

Phosphate-solubilizing bacteria play a significant role in improving growth, yield, and soil health in groundnut cultivation through multiple direct and indirect mechanisms (Alotaibi et al., 2024; Meena et al., 2023). These bacteria act as plant growth-promoting rhizobacteria (PGPR), enhancing nutrient availability, stimulating root development, and improving plant physiological processes under varying soil conditions.

5.1 Enhancement of Phosphorus Availability

PSB convert insoluble forms of phosphorus into plant-available forms, thereby increasing phosphorus uptake and nutrient use efficiency in groundnut (Li et al., 2024; Kumar et al., 2022). This reduces dependence on chemical fertilizers and enhances sustainability (Yang et al., 2025).

5.2 Improvement in Root Growth

PSB stimulate root development by producing plant growth-promoting substances such as auxins, gibberellins, and cytokinins (Adesemoye et al., 2021). These hormones enhance root elongation and branching, thereby improving nutrient and water uptake (Alotaibi et al., 2024).

5.3 Increased Nodulation and Nitrogen Fixation

Improved phosphorus availability due to PSB enhances nodulation and nitrogenase activity in groundnut (Singh and Reddy, 2021). This leads to increased biological nitrogen fixation and improved plant growth (Sharma et al., 2024).

5.4 Enhancement of Yield Attributes

Application of PSB improves yield attributes such as the number of pods per plant, pod weight, and kernel yield (Gentile et al., 2025; Sid et al., 2025). These improvements collectively contribute to higher overall crop productivity (Kumar et al., 2022). This improvement is primarily due to enhanced nutrient uptake and better assimilate translocation, resulting in improved reproductive efficiency and yield formation.

5.5 Improvement in Soil Health

PSB contribute to soil health by enhancing microbial diversity, improving soil structure, and promoting nutrient cycling (Meena et al., 2023). Their continuous application helps maintain long-term soil fertility and supports sustainable agricultural systems (Yang et al., 2025). In addition, PSB enhance soil enzymatic activities such as phosphatases and dehydrogenases, which play a key role in nutrient mineralization and availability. They also promote organic matter decomposition and improve soil aggregation, leading to better soil structure and water retention. These improvements collectively contribute to enhanced soil resilience and long-term sustainability of agro-ecosystems.

VI. EFFECT OF PSB AND PHOSPHORUS ON GROUNDNUT YIELD

Table 1: Effect of Phosphorus and PSB on Yield of Groundnut

Treatment	Pod yield (kg ha^{-1})	Kernel yield (kg ha^{-1})	Increase over control (%)
Control (no P, no PSB)	1850	1150	-
40 kg P_2O_5 ha^{-1}	2450	1550	32.4
40 kg P_2O_5 ha^{-1} + PSB	2650	1725	43.2

Source: Sravani et al. (2025)

The data clearly indicate that the application of phosphorus significantly improves groundnut yield compared to the control. The control treatment (no phosphorus and no PSB) recorded the lowest pod and kernel yields (1850 and 1150 kg ha^{-1}, respectively). Application of 40 kg P_2O_5 ha^{-1} increased pod and kernel yields to 2450 and 1550 kg ha^{-1}, showing a 32.4% improvement over control. However, the combined application of 40 kg P_2O_5 ha^{-1} with PSB resulted in the highest yields (2650 kg ha^{-1} pod yield and 1725 kg ha^{-1} kernel yield), reflecting a 43.2% increase over control. This demonstrates the synergistic effect of phosphorus fertilization and PSB in enhancing nutrient availability, uptake efficiency, and overall crop productivity.

Table 2: Effect of Integrated Nutrient Management

Treatment	Nodules/plant	Pod yield
100% RDF	Moderate	Moderate
75% RDF + PSB	High	High
75% RDF + PSB + AMF	Very High	Maximum

Source: Sanjana et al. (2024)

The results indicate that integrated nutrient management significantly enhances nodulation and yield in groundnut. Application of 75% RDF with PSB increased nodules per plant and pod yield compared to 100% RDF alone, while the combined use of 75% RDF + PSB + AMF resulted in very high nodulation and maximum yield. This highlights the synergistic effect of biofertilizers in improving nutrient efficiency and crop productivity.

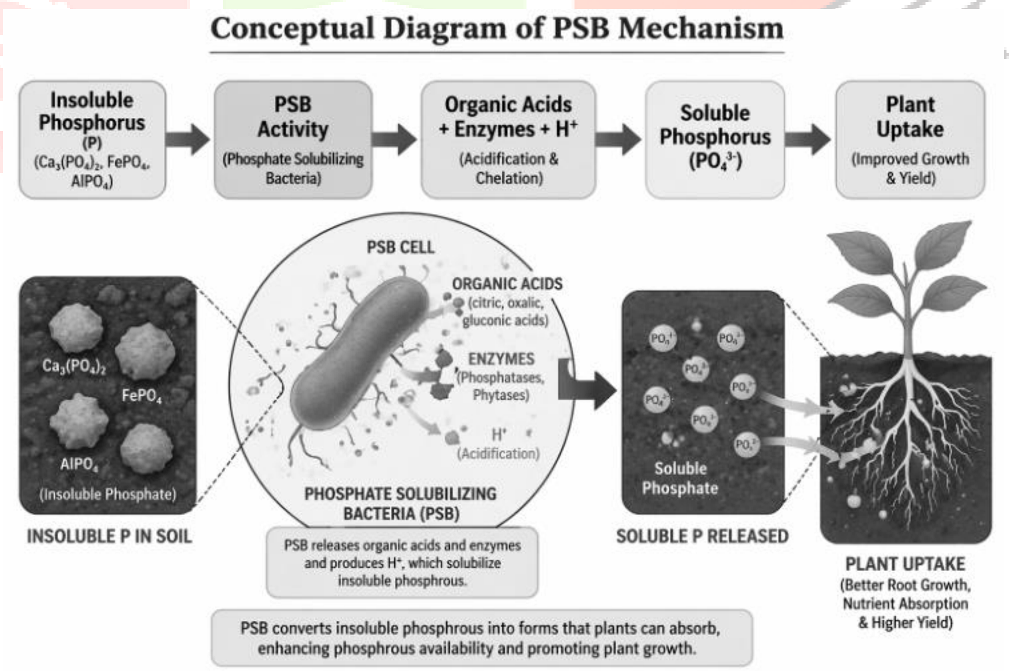

Figure 1. Conceptual diagram illustrating phosphate solubilization mechanisms by phosphate-solubilizing bacteria (PSB) including organic acid production, enzymatic activity, proton extrusion, and chelation processes.

The conceptual diagram illustrates the mechanism by which phosphate-solubilizing bacteria (PSB) enhance phosphorus availability in soil and promote plant growth. In most agricultural soils, a large proportion of phosphorus exists in insoluble forms such as calcium phosphate ($Ca_3(PO_4)_2$), iron phosphate ($FePO_4$), and aluminium phosphate ($AlPO_4$), which are not readily available to plants. PSB colonize the rhizosphere and play a crucial role in converting these unavailable forms into soluble phosphorus. They achieve this through several biochemical processes, including the production of organic acids (such as gluconic, citric, and oxalic acids), which lower soil pH and dissolve phosphate complexes. Additionally, PSB produce enzymes like phosphatases and phytases that mineralize organic phosphorus into inorganic forms. The release of hydrogen ions (H^+) further contributes to acidification, enhancing phosphorus solubilization, while chelation of metal ions (Ca^{2+}, Fe^{3+}, Al^{3+}) helps release bound phosphorus. As a result of these combined actions, insoluble phosphorus is converted into soluble orthophosphate ions (PO_4^{3-}), which are readily absorbed by plant roots. This increased phosphorus availability leads to improved root development, enhanced nodulation and nitrogen fixation in legumes like groundnut, better nutrient uptake, and ultimately higher crop yield and productivity.

VII. DISCUSSION

The integration of phosphorus fertilization with PSB significantly enhances phosphorus availability, root growth, nodulation, and yield in groundnut. Recent studies confirm that PSB can reduce phosphorus fertilizer requirements by up to 25% without compromising yield (Sanjana et al., 2024; Yang et al., 2025). However, under high phosphorus conditions, microbial efficiency may decline due to feedback inhibition, suggesting the need for site-specific nutrient management (García-Berumen et al., 2024). Thus, optimizing PSB application under varying soil conditions is critical for maximizing benefits. The variability in PSB efficiency across soil types highlights the importance of selecting efficient strains adapted to specific agro-ecological conditions. These findings indicate that PSB-based nutrient management can serve as an effective strategy for improving phosphorus-use efficiency and sustaining groundnut productivity under phosphorus-limited conditions, highlighting their potential as a key component of climate-smart agriculture.

VIII. CONCLUSION

Phosphorus is a critical nutrient for groundnut production, but its availability is limited in most soils. Phosphate-solubilizing bacteria offer an eco-friendly and sustainable solution to enhance phosphorus availability. Integration of PSB with phosphorus fertilization improves crop productivity, reduces input costs, and promotes soil health. Future research should emphasize strain-specific efficiency, molecular characterization, and multi-location field validation to ensure large-scale adoption of PSB-based nutrient management strategies.

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