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Combined Application of Phosphorus and Phosphate Solubilizing Bacteria Improves Crop Productivity

Dimpi Jaiswal[1], Priyankar Pal[2*], Bidyut Bandyopadhyay[3]

Articalinfo

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Authors: Dr Priyankar Pal,
E-mail:priyankarpal97@gmail.com

[1]Research Scholar, Department of Microbiology, School of Life Sciences, Swami Vivekananda University Barrackpore 700012, West Bengal, India

[2*]Assistant Professor, Department of Biotechnology, School of Life Sciences, Swami Vivekananda University, West Bengal, India.

[3]Professor & Principal, The Oriental Institute of Science and Technology, Dewandighi, Bardhaman Katwa Rd, Bardhaman, West Bengal 713102, India.

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Abstract

Phosphate-solubilizing bacteria (PSB) play a vital role in enhancing phosphorus (P) availability, a key nutrient required for optimal plant growth, root development, flowering, and yield. Although phosphorus fertilizers are widely used to address soil P deficiencies, much of the applied P becomes soil-bound and unavailable to plants. PSBs help overcome this limitation by converting insoluble phosphorus into plant-available forms, thereby improving nutrient uptake and crop productivity. Research indicates that integrating PSB with phosphorus fertilizers offers a sustainable strategy to boost crop yield, reduce reliance on synthetic inputs, and minimize environmental impacts. However, the success of this approach depends on factors such as soil type, crop species, and environmental conditions, underscoring the need for site-specific management and careful selection of microbial inoculants.

Introduction:

In agricultural systems, phosphorus (P) is a crucial macronutrient essential for the growth and maturation of living organisms (Lareen et al., 2016; Lynch, 2007). As a key component of ATP, it plays a vital role in photosynthesis, respiration, nucleic acid synthesis, phospholipid formation, and nitrogen fixation in plants (Malhotra et al., 2018). Unlike nitrogen (N), phosphorus cannot be biologically fixed from the atmosphere; instead, plants acquire it directly from the soil (Ezawa et al., 2002). Although soils often contain high amounts of total phosphorus, less than 5% is typically available for plant uptake (Lambers, 2022).

By the end of the 21st century, changes in atmospheric conditions—major drivers of geological and soil processes—are expected to increase global temperatures by another 2–3°C, contributing to enhanced soil calcification and salinization (Varallyay, 2010). Elevated CO_2 levels, rising temperatures, drought, irregular precipitation, and atmospheric deposition have already shown adverse effects on soil health (Wixon & Balser, 2009). Consequently, increasing soil salinity and calcification, particularly under arid and changing climatic conditions, may significantly reduce crop yields (Battaglia et al., 2018).

In soils, phosphate ions ($H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}) often become immobilized or form insoluble complexes with cations, limiting their availability to plants (Yadav et al., 2017). Since phosphorus fertilizers are indispensable for global food production (Brindaban et al., 2020; Smit, 2000; Steen, 1998), improving phosphorus-use efficiency is essential.

The excessive use of chemical P fertilizers not only increases production costs but also contributes to environmental pollution, necessitating management strategies to reduce P runoff, protect water bodies, and conserve aquatic ecosystems (Tilman, 2001; Ketterings, 2007; Czymmek, 2020). Rock phosphate (RP), a natural and eco-friendly phosphorus source containing 4–20% P, has proven effective, particularly when directly applied in soils with high P-fixation capacity, improving soil properties and supporting plant growth (R.B.A. Rafael, 2018; Khasawneh et al., 2007). Addressing phosphorus limitations in deficient soils requires exploring sustainable approaches that incorporate natural amendments and organic manures (Khan et al., 2009).

Rhizosphere-dominant soil microbes play an important role in plant development through various symbiotic mechanisms and are recognized as key plant growth-promoting microorganisms (PGPM) (Compant et al., 2019; Hassan, 2017). Since the 1950s, phosphate-solubilizing bacteria (PSB) have been widely applied as biofertilizers to enhance soil fertility, improve nutrient availability, and increase crop productivity (Kudashev, 1956; Krasilinikov, 1957). These bacteria produce organic acids, enzymes, and protons that solubilize insoluble phosphate compounds such as $Ca_3(PO_4)_2$, especially in calcareous soils (Deubel & Merbach, 2005; Chen et al., 2006). By chelating metal cations such as Ca, Fe, and Al, PSBs convert fixed phosphate into plant-available forms. Additionally, they produce plant growth–promoting substances, including phytohormones and siderophores (Kucey et al., 1989), which have been shown to enhance the productivity of cereal and legume crops (Pal et al., 1999; Afzal et al., 2005; Krishnaraj et al., 2014).

Phosphate solubilizing Soil Microbes:

Phosphate-solubilizing bacteria (PSBs) are among the most extensively studied phosphate-mobilizing microorganisms. Alongside PSBs—which constitute roughly 1–50% of the phosphate-solubilizing microflora—a diverse community of soil organisms, including fungi (0.1–0.5%) and other microorganisms such as protozoa and nematodes, contribute to the solubilization, mineralization, and mobilization of phosphorus complexes, thereby enhancing its availability to plants (Tripura et al., 2005; Chen et al., 2006). Numerous PSB species, including *Rhizobium*, *Bacillus*, *Azotobacter*, *Pseudomonas*, *Agrobacterium*, *Enterobacter*, and fungal genera such as *Aspergillus* and *Penicillium*, exhibit high phosphorus-solubilizing and mineralizing efficiencies (Wakelin et al., 2004; Xiao et al., 2011; Park et al.; Kumar et al., 2014; Whitelaw, 2000). Other soil organisms such as protozoa and nematodes also play a role by interacting with soil minerals and organic matter, facilitating the breakdown and release of phosphorus from phosphate rocks (Duponnois et al., 2006).

When combined with phosphorus fertilizers like rock phosphate (RP), microbial activity can create synergistic effects that significantly enhance phosphorus availability, uptake, and use efficiency, especially in soils with high P-fixation capacity (Bargaz et al., 2018; Gupta et al., 2011; Mahanta et al., 2018; Nacoon et al., 2020; Xu Cheng et al., 2019). Irshad and Yergeau (2018) reported that interactions between *Pseudomonas* isolates and nematode grazers markedly improved phosphorus mobilization under RP amendment. The integration of PSBs with RP facilitates the conversion of insoluble phosphate into plant-available forms, stimulates plant growth, improves soil health, and ultimately enhances crop productivity (Sridevi et al., 2007; Manzoor et al., 2017). Moreover, co-inoculation with nitrogen-fixing bacteria and PSBs has frequently proven more effective than single inoculations, offering a more balanced nutrient supply to plants (Belimov et al., 1995). Studies also indicate that supplementing RP–PSB systems with nutrient-rich organic materials such as poultry manure, eggshells, animal bone meal, and composts further enhances microbial activity and phosphorus solubilization potential.

Mechanism of Phosphate Solubilization & Mineralization by PSM

Phosphate-solubilizing bacteria (PSBs) play a pivotal role in enhancing plant-available phosphorus (P) by converting insoluble organic and inorganic P compounds into soluble forms through solubilization and mineralization processes (W. Chen & Y.P., 2016). Phosphate solubilization occurs when insoluble phosphates are transformed into bioavailable forms such as HPO_4^{2-} and $H_2PO_4^-$ via mechanisms including medium acidification, ion exchange, siderophore production, and the secretion of organic acids (Chung et al., 2005; Gulati et al., 2010). A wide variety of organic acids—such as uric, acetic, citric, lactic, propionic, glycolic, oxalic, malonic, succinic, formic, and tartaric acids—have been reported to participate in this process (Ahmed & Shahab, 2011), while gluconic and 2-ketogluconic acids are recognized as the most common and effective agents for mineral phosphate solubilization (Song et al., 2008).

The efficiency of phosphate solubilization depends on both the type and strength of the organic acids produced. Tricarboxylic and dicarboxylic acids generally exhibit higher solubilization potential compared to monobasic and aromatic acids, while aliphatic acids have been shown to outperform phenolic, citric, and fumaric acids in dissolving phosphate minerals (Mahidi et al., 2011). Advanced detection techniques such as HPLC and enzymatic assays provide reliable means for quantifying organic acid production by phosphate-solubilizing microorganisms (Whitelaw, 2000).

Once released into soil or culture media, these organic acids dissociate into anions and protons, establishing a pH-dependent equilibrium that facilitates the dissolution of insoluble phosphates into plant-usable forms (Welch et al., 2002). Additionally, nitrifying and sulfur-oxidizing bacteria contribute to phosphate solubilization by producing inorganic acids—such as nitric and sulfuric acids—during the oxidation of nitrogenous and sulfur compounds, thereby enhancing P availability across diverse ecosystems (Khan et al., 2007).

PSBs also secrete several phosphorus-hydrolyzing enzymes, including phosphatases and phytases, which mineralize organic phosphorus compounds by cleaving phosphomonoester bonds and releasing orthophosphate ions readily absorbed by plants (Trujillo, 2019; Chawngthu, 2020; Paul, 2018). Nevertheless, microbial activity and phosphate-solubilizing efficiency are influenced by multiple environmental factors such as soil moisture, pH, temperature, soil composition, particle size, and the chemical nature of the phosphate substrate.

Impression of psms and phosphorous on agricultural yield

The integration of phosphate-solubilizing microorganisms (PSMs) with plant inoculants offers a sustainable and eco-friendly strategy for improving soil fertility and enhancing crop productivity (Khan et al., 2010; Zaidi et al., 2009). Young et al. (2003) demonstrated that inoculating horticultural plants and vegetables with phosphate-solubilizing bacteria (PSB) led to significant improvements in plant growth and yield. The addition of nutrient-rich organic amendments—such as poultry manure, eggshells, animal bone meal, and compost—further strengthens these beneficial effects.

Studies by Chen et al. (2008) and Wani et al. (2007) highlight that PSB and other rhizosphere-associated microbes exert substantial positive impacts on plant performance when applied individually or in combination in conventional agricultural soils. Through bioformulation, multiple microbial inoculants are incorporated with suitable carriers to establish a stable and protective environment for the microorganisms (Malusá et al., 2012). Common carrier materials in solid and liquid formulations include cottonseed flour, wheat meal, acacia gum, peat, vermiculite, perlite, clay minerals, compost, sawdust, biochar, alginate beads, and synthetic polymers (Mastan et al., 2019). The use of dried starch beads as carriers for PGPR inoculants (De-Bashan, 2002) and the incorporation of mineral clay into alginate matrices have been shown to improve bacterial survival by providing a protective microenvironment (Schoebitz et al., 2013).

PSMs also contribute to enhanced nitrogen fixation by stimulating diazotroph populations, thereby supporting agronomic improvement (Ponmurugan & Gopi, 2006). Son et al. (2006) reported that certain *Pseudomonas* species significantly improved soybean growth and yield, while active PSB strains such as *Pantoea* and *Pseudomonas* demonstrated strong growth-promoting effects on *Pisum sativum* (Anwar et al., 2018). Microbial formulations thus represent a sustainable and environmentally safe method for boosting soil health and crop performance.

Afzal et al. (2005) observed that inoculating wheat (*Triticum aestivum* L.) with phosphate-solubilizing *Pseudomonas* and *Bacillus* strains enhanced phosphorus uptake and significantly increased grain yield. Similarly, Sharma et al. (2007) reported improved seedling length in *Cicer arietinum* (chickpea) following PSB application, and Sundara et al. (2002) documented a 12.6% increase in sugarcane yield in response to PSB inoculation. Collectively, these findings demonstrate the versatility and effectiveness of PSB across diverse crops and agroecosystems, underscoring their potential to strengthen food security and promote sustainable agricultural development.

Conclusion:

When phosphorus-containing fertilizers are applied to soil, a substantial proportion of the phosphorus becomes unavailable for plant uptake because it precipitates with calcium (Ca), iron (Fe), and aluminum (Al) cations. Inoculating soils with phosphate-solubilizing microorganisms (PSMs) can help overcome this limitation by enhancing the solubilization of these insoluble phosphate complexes. The combined use of phosphorus fertilizers and phosphate-solubilizing bacteria (PSB) offers economic advantages to farmers by improving crop yields while reducing reliance on chemical fertilizers. Integrated nutrient management strategies that incorporate PSB formulations alongside conventional fertilizers can improve soil structure, enhance crop productivity, and support environmental sustainability in agriculture.

Within this context, three key research priorities have emerged for maximizing microbial phosphorus solubilization in sustainable crop production:

1. **Optimizing integration strategies** for combining PSB with phosphorus fertilizers;
2. **Developing innovative culture-dependent screening techniques** to improve the identification and selection of efficient bacterial strains; and
3. **Assessing long-term sustainability**, ensuring that PSB-based approaches maintain soil health and productivity over time.

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