A Review on Phosphate-Solubilizing Rhizobacteria

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Abstract:
Phosphorus (P) is the second-most important element after nitrogen that is required for plant growth. Although this element is abundant in most soils, it is rarely available in plant-accessible forms since most of it normally exists in soil in insoluble forms such as phosphates. In conventional agriculture, P is normally supplied as chemical fertilizer to satisfy plant P requirements. This, to a large extent, boosts plant production. However, chemical fertilizers are costly, have a huge carbon footprint, and are environmentally-un sustainable owing to the high energy requirements during their synthesis.

Keywords: Phosphorus solubilization; plant growth promotion; biofertilizers; sustainable agriculture; phosphorus solubilizing bacteria; rhizobacteria

I. INTRODUCTION
Phosphorus (P) is the second-most important nutrient after nitrogen in terms of plant growth and development. This nutrient element is important in virtually every metabolic process in plants from photosynthesis, biosynthesis of macromolecules, and respiration to energy transfer and signal transduction. It is a fundamental component of enzymes, proteins, coenzymes, nucleotides, phospholipids, and nucleic P availability also improves other basic plant functions such as cell division, cell enlargement, and transformation of starches and sugars. Although P is present in most soils in large quantities, its accessibility to plants is largely limited since it occurs in complex and insoluble forms, and only about 0.1% is available for plant use (Alori et al., 2017; Zhu et al., 2011). According to Mahidi et al., (2011) and Alaylar al (2020), P anions are highly reactive get immobilized through complex formation with different cations like Mg, Al, Ca, and Fe, especially under low pH and the fraction that is available to plants is generally very low. Consequently, P is often a major limiting plant nutrient in most soils (Santana et al., 2016), and artificial P fertilizers have for long been employed to cater for P deficits in agricultural farms (Mitra et al., 2020; S. B. Sharma et al., 2013). According to FAO, (2017) approximately 52.3 billion tons of P-based fertilizers are applied each year in agricultural lands. These synthetic fertilizers present a lot of problems in the environment. For instance, increased P from agricultural farms has been identified as a major course of eutrophication and rapid becoming fixed or immobilized in soils and has long-term impacts on the environment in terms of eutrophication, soil fertility depletion, and carbon footprint (S. B. Sharma et al., 2013; Zhang et al., 2017). Moreover, P is a finite resource and due to its great demand, and it is estimated that the word’s known reserves could be depleted (Leghari et al., 2016) in the current century (Cordell et al., 2009). The realization of the aforementioned potential problems associated with chemical P fertilizers, together with the high costs involved in their manufacture has led to the search for alternative plant fertilization mechanisms (Alori et al., 2017; Zaidi et al., 2009). Plant Growth-Promoting Rhizobacteria (PGPR) are plant-root residing bacteria in symbiotic interactions that have for decades been investigated as alternative environmentally friendly and cheap plant fertilization tools (P. N. Bhattacharyya et al., 2016; P. N. Bhattacharyya & Jha, 2012). Phosphate solubilizing bacteria (PSB) are a subset of the PGPR with the ability to solubilize complex P forms into plant-accessible forms (Pande et al., 2017; Zaidi et al., 2009). Although a lot of research has been done on different nutrients-solubilizing rhizobacteria and their potential in sustainable agriculture (Chen et al., 2006; M. S. Khan et al., 2010), their mechanisms of action and prospects in sustainable agriculture remain to be fully understood. This review focuses on the diversity, mechanisms of action, and prospects of PSB in sustainable agriculture based on the present and future scenario of their application. Such information is useful in determining their potential and evaluating their prospects in promoting sustainable agricultural systems.

The diversity of P solubilizing Rhizobacteria
Numerous microorganisms, including fungi, are capable of releasing P from soil through solubilization and mineralization in the natural soil environment (Alori et al., 2017; P. N. Bhattacharyya & Jha, 2012; Kafle et al., 2019). It is estimated that 50% of all bacteria in soil are capable of solubilizing P (S. B. Sharma et al., 2013), and several strains of rhizobacteria have been described and investigated in detail for their P solubilizing
capabilities. According to Sharma et al., (2013), these organisms are ubiquitous but vary in density and P solubilizing abilities from soil to soil (Awais et al., 2019; Chen et al., 2006; Kalayu, 2019; Vessey, 2003). These bacteria can be isolated from rhizospheres, rhizoplane, and even non-rhizosphere soils (S. B. Sharma et al., 2013; Zaidi et al., 2009). However, they are known to be more metabolically active and better P solubilizers in plant rhizospheres (P. Kaur & Purewal, 2019; A. A. Khan et al., 2009; Rafi et al., 2019; Vessey, 2003).

Mechanisms of P solubilizing Plant Root Residing Bacteria
The mechanisms of P solubilization depends on the P forms in soil, whether organic or inorganic. While inorganic P forms occur in soil as insoluble mineral complexes, mostly after the application of chemical fertilizers, organic P is mostly constituted in organic matter (S. B. Sharma et al., 2013). According to Alori et al., (2017), organic P can be as high as 30 - 50% of the total P in soil. The most common form of organic P is phytate/inositol P but are largely unavailable to plants because they lack phytase activities (Alori et al., 2017; Kafle et al., 2019; A. Kumar, 2016). Other organic P compounds that have include phosphomonoesters, phosphodiesters, phospholipids, nucleic acids, and phosphotriesters (A. Kumar, 2016). Rhizobacteria of many plants have been shown to possess the ability to mineralize both organic and inorganic complex P compounds. For instance, the ability of several rhizobacterial genera to solubilize inorganic P compounds such as tricalcium phosphate, dicalcium phosphate, and rock phosphate is largely documented (Billah et al., 2019; El-Deen et al., 2020). From experiments, the principal mechanism is the production of mineral dissolving compounds such as organic acids, siderephores, protons, hydroxyl ions, and CO₂ (Satyaprakash et al., 2017; S. B. Sharma et al., 2013). Nevertheless, the main mechanism of inorganic P solubilization is largely proposed to be by organic acids (Billah et al., 2019; Pande et al., 2017; Rafi et al., 2019; Walia et al., 2017), whose carboxyl and hydroxyl ions act by lowering soil pH, chelating cations like iron, aluminum, and calcium ions bound to P, competing with P for adsorption sites in soil and/or forming soluble complexes with metal ions associated with P (P. N. Bhattacharyya et al., 2016; Billah et al., 2019; S. T. Patel & Minocheheromjii, 2018; Pradhan et al., 2017; S. B. Sharma et al., 2013). These acids that compete for fixation sites of Al and Fe insoluble oxides are called chelates (Kulayu et al., 2019). One such acid which is a powerful chelator of calcium is 2-ketogluconic acid (Walpola & Yoon, 2013). Organic acids may also directly dissolve mineral P by anion exchange (Satyaprakash et al., 2017). These acids are products of microbial metabolism such as oxidative respiration or fermentation of organic sources (Satyaprakash et al., 2017; Zaidi et al., 2009). The organic acids that solubilize phosphates are primarily citric, lactic, gluconic, 2-ketogluconic, oxalic, glycolic, acetic, malic, fumaric, succinic, tartaric, malonic, glutaric, propionic, butyric, glyoxylic, and adipic acid (A. Kumar et al., 2018; Satyaprakash et al., 2017). Others include isovaleric acid, lactic acid, isobutyric acid, and oxalic acid (C. Kaur et al., 2016; Rawat et al., 2018). Table 2 shows different forms of organic acids produced by several PSB associated with different plants. Among these organic acids, gluconic acid is the most common one implicated in P solubilization (Alori et al., 2017; S. B. Sharma et al., 2013). Different organisms produce different types and quantities of organic acids (Kalayu, 2019; Rafi et al., 2019; Satyaprakash et al., 2017), which is also dependent on the type of carbon available for the microbes (D. Patel & Goswami, 2020). Subsequently, they differ extensively in their P solubilization efficiency (Rafi et al., 2019). (Kalayu, 2019). A second and major component of soil P is organic matter which contains organic P forms which may constitute 15 - 85% of the total P in most soils The solubilization of organic P forms occurs through mineralization by several PSB. The mineralization process is mediated by enzymes such as phosphatases and phytases. Phosphatases, which may be acid or alkaline in nature based on their pH optima, are nonspecific enzymes that are secreted by bacterial cells and require P as substrates. Apart from inorganic P solubilization by acidification and organic P solubilization by bacterial enzymes, several other bacterial mechanisms have also been suggested to bring about P solubilization. One important theory of the solubilization of organic P is the sink theory. Microorganisms in the presence of labile C serve as a sink for P, by rapidly immobilizing it even in low P soils; PSB become a source of P to plants upon its release from their cells. Release of P immobilized by PSB primarily occurs when cells die due to changes in environmental conditions, starvation, or predation. Apart from this, bacterial siderophores which are complexing agents with a high affinity for iron have also been considered to take part in P solubilization. However, this mechanism of P solubilization has not been widely investigated, and the production of siderophores by PSB has not yet been directly linked to PSB solubilization. Considering the dominance of mineral dissolution over ligand exchange by organic acid anions as a P solubilization mechanism the potential role of siderophore in P solubilization should be given more attention. Microbial exopolysaccharides (EPS) which are polysaccharide polymers excreted by microbes into their environment have also been linked to P solubilization. The authors established a strong indication of P solubilization by Arthrobacter, Azotobacter, and Enterobacter spp. that produced EPS were also shown to increase the quantities of soluble P. This is indeed an interesting phenomenon but more studies are necessary to understand the relationship between EPS production and phosphate solubilization. It is clear that P solubilization by PSB has been a subject of analysis and research for a long time and yet still seems to be in its infancy. It occurs through different mechanisms and there is considerable variation amongst the organisms in this respect. Each organism can act in one or more than one way to bring about the solubilization of insoluble P. Though it is difficult to pinpoint a single mechanism, the production of organic acids and consequent pH reduction appears to be of great importance.

Prospects of P solubilizing Rhizobacteria in Sustainable Agricultures
There is no doubt that artificial P fertilizers can improve plant mineral P nutrition but the resources used to make these fertilizers are finite and dwindling. Moreover, P availability to plants is still limited even in chemical-P supplied soils due to fixation. About 75 – 90% of the added chemical P fertilizer is precipitated by metal-cation complexes and rapidly becomes fixed in soils and has long-term impacts on the environment in terms of eutrophication, soil fertility depletion, and carbon footprint. For decades, researchers worldwide have vigorously been searching for alternative plant fertilization mechanisms. This has paved ways for the identification of efficient PGP

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rhizobacteria and their development into biofertilizers by formulating them into different carrier materials. The use of such organisms is greatly advocated for in this regard because they are environmentally friendly and relatively cheap compared to their artificial counterparts. According to these microorganisms can also protect plants against phytopathogens and have a high cost-benefit ratio because of low-cost production technologies. This is because their formulation largely involves the use of agribusiness waste products which are readily and cheaply available. The use of these waste products in the formulation of biofertilizers including the PSB not only contribute to environmental sustainability by providing eco-friendly plant fertilization mechanism but also by reducing the quantity of wastes in the environment. Microorganisms are an integral part of the phosphorus cycle, and the beneficial effects of PSB inoculation have been described in many plants and they are already being applied as effective inoculants in agronomic practices to increase the productivity of many crops. According to Alori et al., the PSB technology can improve soil fertility and help in the realization of sustainable agriculture with minimized usage of artificial fertilizers and P use efficiency in agricultural lands can be improved through inoculation of PSM. Several PSB are commercially available in the market as formulated products or biofertilizers. The first commercial biofertilizer called “Phosphobacterin” was formulated using Bacillus megaterium var. phosphaticum in the former Soviet Union and later on was frequently applied in East European countries and India. presents forms of commercially available PSB biofertilizers in different countries and their trade names. Although several Gram-negative PSB such as Pseudomonas are known to competent P solubilizers, their formulation into biofertilizers is problematic because they do not bear spores, thus, have short shelf lives.

II. REFERENCES


