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REVIEW

Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective

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Abstract Plant growth promoting rhizobacteria are the soil bacteria inhabiting around/on the root surface and are directly or indirectly involved in promoting plant growth and development via production and secretion of various regulatory chemicals in the vicinity of rhizosphere. Generally, plant growth promoting rhizobacteria facilitate the plant growth directly by either assisting in resource acquisition (nitrogen, phosphorus and essential minerals) or modulating plant hormone levels, or indirectly by decreasing the inhibitory effects of various pathogens on plant growth and development in the forms of biocontrol agents. Various studies have documented the increased health and productivity of different plant species by the application of plant growth promoting rhizobacteria under both normal and stressed conditions. The plant-beneficial rhizobacteria may decrease the global dependence on hazardous agricultural chemicals which destabilize the agro-ecosystems. This review accentuates the perception of the rhizosphere and plant growth promoting rhizobacteria under the current perspectives. Further, explicit outlooks on the different mechanisms of rhizobacteria mediated plant growth promotion have been described in detail with the recent development and research. Finally, the latest paradigms of applicability of these beneficial rhizobacteria in different agro-ecosystems have been presented comprehensively under both normal and stress conditions to highlight the recent trends with the aim to develop future insights.

1. Introduction

Different bacterial genera are vital components of soils. They are involved in various biotic activities of the soil ecosystem to make it dynamic for nutrient turn over and sustainable for crop production (Ahemad et al., 2009; Chandler et al., 2008). They stimulate plant growth through mobilizing nutrients in soils, producing numerous plant growth regulators, protecting plants from phytopathogens by controlling or inhibiting them, improving soil structure and bioremediating the polluted soils by sequestering toxic heavy metal species

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Table 1 Various compounds in root exudates of different plant species.

Amino acids	α-Alanine, β-alanine, asparagines, aspartate, cystein, cystine, glutamate, glycine, isoleucine, leucine, lysine, methionine, serine, threonine, proline, valine, tryptophan, ornithine, histidine, arginine, homoserine, phenylalanine, γ-Aminobutyric acid,α-Aminoadipic acid
Organic acids	Citric acid, oxalic acid, malic acid, fumaric acid, succinic acid, acetic acid, butyric acid, valeric acid, glycolic acid, piscidic acid, formic acid, aconitic acid, lactic acid, pyruvic acid, glutaric acid, malonic acid, tetronic acid, aldonic acid, erythronic acid
Sugars	Glucose, fructose, galactose, ribose, xylose, rhamnose, arabinose, desoxyribose, oligosaccharides, raffinose, maltose
Vitamins	Biotin, thiamin, pantothenate, riboflavin, niacin
Purines/nucleosides	Adenine, guanine, cytidine, uridine
Enzymes	Acid/alkaline-phosphatase, invertase, amylase, protease
Inorganic ions and gaseous molecules	HCO_3^-, OH^-, H^+ $CO_2{\cdot}H_2$

Adapted from Dakora and Phillips (2002).

and degrading xenobiotic compounds (like pesticides) (Ahemad, 2012; Ahemad and Malik (2011); Hayat et al., 2010; Rajkumar et al., 2010; Braud et al., 2009). Indeed, the bacteria lodging around/in the plant roots (rhizobacteria) are more versatile in transforming, mobilizing, solubilizing the nutrients compared to those from bulk soils (Hayat et al., 2010). Therefore, the rhizobacteria are the dominant deriving forces in recycling the soil nutrients and consequently, they are crucial for soil fertility (Glick, 2012). Currently, the biological approaches for improving crop production are gaining strong status among agronomists and environmentalists following integrated plant nutrient management system. In this context, there is an ongoing rigorous research worldwide with greater impetus to explore a wide range of rhizobacteria possessing novel traits like heavy metal detoxifying potentials (Ma et al., 2011a; Wani and Khan, 2010), pesticide degradation/tolerance (Ahemad and Khan, 2012a,b), salinity tolerance (Tank and Saraf, 2010; Mayak et al., 2004), biological control of phytopathogens and insects (Hynes et al., 2008; Russo et al., 2008; Joo et al., 2005; Murphy et al., 2000) along with the normal plant growth promoting properties such as, phytohormone (Ahemad and Khan, 2012c Tank and Saraf, 2010), siderophore (Jahanian et al., 2012; Tian et al., 2009), 1-aminocyclopropane-1-carboxylate, hydrogen cyanate (HCN), and ammonia production, nitrogenase activity (Glick, 2012; Khan, 2005) phosphate solubilization (Ahemad and Khan, 2012c) etc. Hence, diverse symbiotic (*Rhizobium*, *Bradyrhizobium*, *Mesorhizobium*) and non-symbiotic (*Pseudomonas*, *Bacillus*, *Klebsiella*, *Azotobacter*, *Azospirillum*, *Azomonas*), rhizobacteria are now being used worldwide as bio-inoculants to promote plant growth and development under various stresses like heavy metals (Ma et al., 2011a,b; Wani and Khan, 2010), herbicides (Ahemad and Khan, 2011l; Ahemad and Khan, 2010g), insecticides (Ahemad and Khan 2011h,k), fungicides (Ahemad and Khan, 2012f; Ahemad and Khan, 2011j), salinity (Mayak et al., 2004) etc.

Although, the mechanisms of rhizobacteria-mediated plant growth promotion are not completely identified, the so-called plant growth promoting rhizobacteria however, have been reported to exhibit the above mentioned properties to expedite the plant growth and development (Khan et al., 2009; Zaidi et al., 2009). The present review is an effort to elucidate the concept of rhizobacteria in the current scenario and their underlying mechanisms of plant growth promotion with recent updates. The latest paradigms of a wide range of applications of these beneficial rhizobacteria in different agro-ecosystems have been presented explicitly to garner broad perspectives regarding their functioning and applicability.

2. Rhizosphere

The narrow zone of soil directly surrounding the root system is referred to as rhizosphere (Walker et al., 2003), while the term 'rhizobacteria' implies a group of rhizosphere bacteria competent in colonizing the root environment (Kloepper et al., 1991). In addition to providing the mechanical support and facilitating water and nutrient uptake, plant roots also synthesize, accumulate, and secrete a diverse array of compounds (Walker et al., 2003). These compounds secreted by plant roots act as chemical attractants for a vast number of heterogeneous, diverse and actively metabolizing soil microbial communities. The chemicals which are secreted by roots into the soils are generally called as root exudates. The exudation of a wide range of chemical compounds (Table 1) modifies the chemical and physical properties of the soil and thus, regulates the structure of soil microbial community in the immediate vicinity of root surface (Dakora and Phillips, 2002). In fact, some of the exudates act as repellants against microorganisms while others act as attractants to lodge the microbes. The composition of these exudates is dependent upon the physiological status and species of plants and microorganisms (Kang et al., 2010). Moreover, these exudates also promote the plant-beneficial symbiotic interactions and inhibit the growth of the competing plant species (Nardi et al., 2000). Also, microbial activity in the rhizosphere affects rooting patterns and the supply of available nutrients to plants, thereby modifying the quality and quantity of root exudates. A fraction of these plant-derived small organic molecules is further metabolized by microorganisms in the vicinity as carbon and nitrogen sources, and some microbe-oriented molecules are subsequently re-taken up by plants for growth and development (Kang et al., 2010). Indeed, carbon fluxes are critical determinants of rhizosphere function. It is reported that approximately 5–21% of photosynthetically fixed carbon is