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Plant Growth Promoting Rhizobacteria (PGPR): A Bioprotectant bioinoculant for Sustainable Agrobiology. *A Review*

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Abstract

Plant growth promoting rhizobacteria (PGPR) involves the utilization of large array of soil bacteria to improve yield and plant growth. As free living and symbiotic rhizobacteria, PGPR colonizes extracellular and/or intracellular rhizoenvironment in search for carbon source while indirectly aiding plant growth. In the past few decades, focus has been on developing a biosafety agro base approach void of continuous burden on soil micro flora as a result of agrochemical application. However, with clear understanding of PGPR mechanisms of action; (i) biofertilization (ii) biostimulation (iii) and biocontrol, it create more hope on the possibility of curbing food insecurity, clean environmental sustenance and lower public health risk. Seeds or soil application of PGPRs inoculant enhances directly phosphates solubilization, atmospheric nitrogen fixation and secretion of plant hormones (indole acetic acid, gibberellins, cytokinins and ethylene) needed for growth and adaptation in stressed environment. As soil pathogen consistently rival the roles of these organisms, they (PGPRs)have developed over time wide spectrum of strategies in the form of systemic resistance, iron, space and nutrient competition, antibiotics synthesis, lytic acid production and hydrogen cyanide for efficient food productivity. In view of this, the review widen our scope on the use of PGPR as bioinoculant in sustainable agro practice and to serve as a wakeup call for it reception and implementation in the tropics where paucity of data on it use has long prevailed.

Keywords: Plant growth promoting rhizobacteria (PGPR), biofertilization, biostimulation, biocontrol, agrobiology, bioinoculant, plant hormones.

Introduction

The word “sustainable agrobiology” has been a resounding phrase among policy makers, relevant agencies and international organizations over the past decades. This has becomes ultimately, one of the world most fundamental need to control food insecurity as human population is estimated to hit eight billion in the year 2020 (Glick, 2012).In the last century, man has slowly gotten close to be faced with the greatest challenge of all time (food insecurity), with possible looming consequences on the entire human race if concerted effort is not taken. Overcoming this challenge also will not be an easy task as there has been so much pressure in our natural ecosystem and resources (use of plant for bioethanol) (Iordanis, 2013). More so, as the soil ecology remain highly stressed leading to low yield of agricultural products. Agriculture has remain the main stream of economic activities within the third world, especially in Sub-Sahara Africa. Accompanied with the emergence of mechanize process (Industrialized agriculture), the soil unceasingly welcome fossil fuel use for powering plants, agro-chemicals (pesticides and herbicides), contaminated sewage sludge use for irrigation, and excessive application of fertilizers. To this effect, these practices do not only leave an indelible mark on the soil environment, but alters microbial population which aid plant growth. The use of synthesized agro chemicals and fertilizers has been a point of discuss in the public domain in the time past. Though their advantage tend to be immediate, they still renders a lasing environmental and public health threat to man by (1) possible entrance of heavy metals to the food chain, (2) death of soil biotic life (3) environmental deterioration and degradation and (4) alteration or damage of soil structure (Alalaoui, 2007).

Report indicates that soil harbors millions of diverse groups of microorganisms. These organisms ranges from bacteria, fungi, actinomycestes, algea, nitrogen fixers etc. Since the inception of microbiological research, only about 1% of the estimated number of these organisms has so far been isolated and identified, leaving us with large array of microbes that their existence can only be imagined. Additionally, these organisms live in complex biological communities within which exist interactions arising from other living and non-living influences (Petersen and Klug, 1994). Investigation has revealed that a teaspoon of a healthy soil may contain between 100 million and 1 billion individual cells, thus justifying their possible fast proliferation and adherence of soil organisms to the thin water film around soil particles and near roots rhizosphere of a plant. In combating food security through agrobiology, there is need to lay attention toward the engineering of beneficial microorganisms residence in the soil that have over the years been ascribed with potentials of mitigating associated difficulties in agricultural practice. Hence recommending their utilization in environmental cleanup (Van-Veen *et al*., 1997), renewable energy (Jackson, 1999) and attainment of sustainable agricultural practices (Noumavo *et al*., 2016).

For any nation to attain self-sufficiency in food production, an overhaul of her routine workouts especially in the use of agro chemical (fertilizer, herbicide and pesticides) is vital. Employing the use of biological base product other than synthetic chemicals will not only help in increasing soil fertility but double the revenue base of farmers and the country's GDP through high quality yield, while aiding in ameliorating the damaging effect the chemicals renders on soil ecology. This is necessary in addressing the effects of climate change on food security as identified by Committee on world food security (CFS, 2012). Albeit PGPR inoculant mechanisms of action for increased food production both at present and in the near future has been stressed. It application and operation within the tropics has not been embrace or gotten public acceptance as a result of information gap. This review is therefore aim at exploring how PGPR suppresses phytopathogens while aiding plant growth through biofertilization and phytostimulation and potential of it application and commercialization within the tropics.

Rhizosphere

Over a century, the word rhizosphere has referred to microbial population inhabiting within the immediate region of plant root. This region is a host to divers group of microorganisms that are influenced by rich source of nutrients obtain through the root exudates (Hiltner, 1904). The subdivided of rhizosphere into three separate parts, first the exorhizosphere relates to soil adherent to the root and those attached even after vigorous shaking, the second is rhizoplane which illustrate the thin layer of soil-root and thirdly an intercellular space in the root tissues inhabited by endophyte bacteria (endorhizosphere)was reported by Bowen and Rovira, (1999). These sites encourages healthy competition among organisms for more competency, saprophytic abilities and potential for enhancing plants growth. In addition, it successful organisms multiply easily through a broad spectrum of actions as a result of high nutrient and carbon source, compete favourably with other microorganisms and poses tolerance to drought (Ngumbi and Kloepper, 2016).Additionally, they show high resistance to environmental stress such as desiccation, heat, oxidative agents, heavy metals and crude oil pollution and UV radiation (Nakkeeran et al., 2005). Since the rhizosphere is very rich in nutrients, it associate bacteria (rhizobacteria) tend to developed a unique means of communication by enabling the effective selection of it mutual partner by creating host specificity and selective sensitive environment where diversity is less (Sivasakthi et al., 2014).

Rhizobacteria in the Rhizosphere and Rhozospheric Microflora of Bulk Soil

Bacteria fund over 95% of the soil microbial activities and dominate also in the level of abundant. This credit is as a result of their fast proliferation and ability to utilize wide range of carbon and nitrogen source as energy (Glick, 2012).The rhizobacteria concentration in the rhizosphere is estimated to be about 10^{12} CFU/g of soil (Foster, 1988) while the rhizospheric flora which occurs few distance around the root system (Compant et al., 2010), contains fairly large amount of microbial population;10^{8} -10^{9} CFU/g of soil (Schoenborn et al., 2004). Under intense environmental stress, rhizobacteria population in the soil ecosystem might be drastically reduced to 10^{4} CFU/g of soil (Timmusk et al., 2011). Microbial structure of the bulk soil flora and rhizobacteria differs with the plant developmental stage, specie type, and soil property (Broeckling et al., 2008). Some of the interactions that occur within the rhizosphere and the rhizospheric bulk soil can be said to be either neutral, synergistic or antagonistic. The participating genera involve in harmful interaction tend to work against the plant growth as they exert effect in the form of phytopathogen while the beneficial once enhances plant growth with the ability to support it nutritional provision using different mechanisms (Ahemad and Khan, 2011; Mahdi *et al*., 2010).

Plant Growth Promoting Rhizobacteria (PGPR)

The word PGPR was proposed by Kloepper et al. (1980). It was coin for fluorescent *Pseudomonas*, a plant growth enhancer that fought against pathogens. Since then, the term has metamorphose and extended to include all rhizobacteria capable of directly enhancing plants growth (Kapulnik et al. 1981). Of recent, it was used to include wide range of rhizobacteria that improve plant growth through different mechanisms such as *Alcaligenes*, *Pseudomonas*, *Azospirillum*, *Bacillus*, *Klebsiella*, *Azotobacter*, *Enterobacter*, *Burkholderia*, *Arthrobacter*, and *Serratia* (Saharanand Nehra, 2011; Haghighi et al., 2011) (Table 1). Even though there exist those who are pathogenic to their non-host plants, a good number of them exist in a mutual interaction as they rely on the plant exudate as source of carbon (Penrose and Glick 2001).PGPR exhibit a special role by hindering plant infestation with disease, increase nutrient absorption, encourage root and shoot formation, improve seed germination and making the plant more tolerant to most environmental stress (Lugtenberg and Kamilova 2009; Arora et al. 2008).Interestingly, these organisms have been accrue with fascinating roles ranging from improved nitrogen fixation through nodule formation, solubilization of phosphates, production of phytohormones such gibberellins, siderophores and indole acetic acid, serving as low molecular weight compounds that modulate plant growth and development (Ma et al. 2009). They are categorized into two major groups; (1) symbiotic rhizobacteria which invade the interior/inside of the cell (intracellular PGPR, e.g., nodule bacteria), and (2) free-living rhizobacteria that exist outside the plant cells (extracellular PGPR, e.g., *Bacillus*, *Pseudomonas*, *Burkholderia*, and *Azotobacter*) (Babalola and Akindolire 2011; Khan 2005).

Table 1: Plant growth promoting rhizobacteria and its associated growth-regulating compounds.

Organisms	Regulating compound	References
Brevibacillus brevis	Indole acetic acid (IAA)	Vivas et al., 2006
Pseudomonas fluorescence	Siderophore	Khan et al., 2002
Kluyvera ascorbata	Siderophore	Burd et al., 2000
Bacillus subtilis	IAA and phosphate solubilization	Zaidi et al., 2006
Pseudomonas spp	IAA, siderophore and P-solubilization	Li and Ramakrishna et al. 2011
Microbacterium G16	IAA, siderophores	Sheng et al., 2008
Micrococcus luteus	IAA, P-solubilization	Antoun et al., 2004
Pseudomonas spp.	Phosphate solubilization	Yu et al., 2012
Achromobacter xylosooxidans	IAA, P solubilisation	Ma et al., 2009

Plant Growth Promoting Rhizobacteria in Agriculture

Agriculture is an age long practice, it involve the tilling of land and rearing of livestock for food and economic growth. This practice is considered to be the most important human occupation within the tropics, with over 70% of land in use for this purpose (Khan *et al.*, 2014). Rhizobacteria through the improvement of plant growth, synthesis some secondary metabolites such as phytohormone, enzymes, siderophores, and antibiotics (Noordman et al. 2006; Ahmad et al. 2008), which areneeded for the formation of specific enzymes required for plant growth and biochemical change.

They help in fixing atmospheric nitrogen, provide nutritional uptake by solubilizing phosphate and producing biologically active molecules which influence plant growth (Arshad and Frankenberger, 1992).Studies has shown that for PGPR to be utilized in crop production, it must be able to exert it effects in either one of these three ways; firstby providing the plant with growth-promoting compounds (Glick 1995), secondly by uptake of certain essential nutrients such as phosphorus, nitrogen, sulfur, calcium and magnesium, (Bashan and Levanony 1990; Belimov and Dietz 2000; Cakmakci et al. 2006) and thirdly by averting plants diseases (Khan et al. 2002; Lugtenberg and Kamilova 2009).The demonstration of increased growth and productivity of many commercial crops including maize (Sandhya *et al*., 2010), rice (Ashrafuzzaman *et al.,* 2009), black pepper (Dastager *et al*., 2010), wheat (Cakmakcı *et al.*, 2007), sugarcane (Sundara *et al.,* 2002), cotton (Anjum *et al.*, 2007), Banana (Mia *et al*., 2010), and cucumber (Maleki *et al*., 2010) and those seen in Tables 2 has given credit to this biotechnology. There has been public call for possible exploitation of their role in biofertilizers production, microbial rhizoremediation and biopesticides synthesis (Adesemoye *et al*., 2008).

Table 2: Some of the plant growth promoting rhizobacteria and its associated host plants

Genus	Number of specie	Host plants
Azorhizobium	2	Sesbania
Rhizobium	33	Pisum, Phaseolus
Sinorhizobium	12	Acacia, Medicago
Bradyrhizobium	8	Glycine, Pachyrhizus
Mesorhizobium	19	Cicer, Prosopis

Rivas *et al.* (2009)

Mechanisms of Action

In recent time, scientist have tried to categorize these actions base on the form of exciting growth or benefit it render to plants, either by directly providing the plant with needed compound or indirectly preventing the deleterious effects of one or more phytopathogenic organisms via production of antagonistic substance (Glick, 1995). The positive interactions of PGPR in the form of biofertilization, stimulation of root growth, rhizo-remediation, phytohormones production, plant stress control and efficient uptake of certain nutrients from the environment can be said to be a direct form of its mechanism. While reduction in the impact of diseases, through antibiotic production, antifungal metabolites, induction of systemic resistance, and competition for nutrients and niches are indirect action exhibited by PGPR (Egamberdieva and Lugtenberg, 2014; Pliego et al. 2011; Glick, 1995). Generally, PGPR function by synthesizing particular compounds or phytohormones for the plants (termed "Biostimulants"), facilitating the uptake of certain nutrients from the environment (termed "Biofertilization") and preventing the plants from diseases (termed "Bioprotectants or Biocontrol") (Glick et al., 1998).Advances in this field has implicated PGPR in growth promotion of soil stabilizing plants in controlling flood related issues, aid plant growth in acidic conditions, overturn high temperature stress and used in phytoremediation technologies (Burd et al., 2000; Zhuang et al., 2007).

BIOFERTILIZATION

This is the application of microbial inoculant or microbial base substance on seeds, plant surfaces, or soil to colonize the rhizosphere or the interior part of the plant. This action enhances growth through the supply and availability of primary nutrients to the plant. Bhardwaj, *et al*., (2014) and Arora, *et al*., (2012) identified it role on atmospheric nitrogen fixation, mineralization of organic compounds and phytohormones synthesis. Biofertilizers are essential components of organic agriculture and are vital in maintaining long-term soil fertility and sustainability through the production of safe and healthy food. Mahdi et al. (2010) in their view defined it as cultures of bacteria, fungi and algae either alone or in combination, packed in a carrier material. With scientific research and campaign to halt the over dependent on chemically synthesized fertilizers for agricultural purpose, focus has been on harnessing the potential microorganisms for improve agro practices (Afzal and Asghari, 2008). Generally, the use of chemical base fertilizer to enhance soil fertility and crop yield has often negatively imping the complexity of both biotic and abiotic matter turnover (Perrott *et al*., 1992; Steinshamn *et al.*, 2004), this is because of possible leaching and run-off of nutrients especially Phosphorus (P) and Nitrogen (N) resulting to deteriorated environment (Tilman, 1998; Gyaneshwar *et al.*, 2002). Iordanis et al. (2013) opined that for an efficient biofertilizer to be formed and utilize, there must be proper preparation/formulation of the inoculant, selection of adequate carrier and designing of correct delivering method. However to achieve this, a scientific base research must be done to optimize this technology for commercial application. Hence, increasing productivity through low cost and supporting economic viability for both small and marginal farmers (Boraste *et al.*, 2009).

Nitrogen fixation

Nitrogen (N) is a vital element for all forms of life, it is the most important nutrient for plant growth. Nitrogen is an essential constituent of nucleotides, membrane lipids and amino acids (Marschner, 1995). It constitute the fourth most important plants dry mass. The biological fixation of atmospheric nitrogen is an important microbial activity for the maintenance of life on earth through photosynthesis performed by photosynthetic organisms. This process occurs when atmospheric nitrogen is converted to ammonia by an enzyme called nitrogenase; a highly complex oxygen labile enzyme conserved in free-living symbiotic diazotrophs (Franche *et al*., 2009). The process is coupled with the hydrolysis of 16 equivalents of ATP and is accompanied by the co-formation of one molecule of H_2. Considering the two types of nitrogen fixation (symbiotic and non-symbiotic process) base on the plant involve and the associated group of organisms, it is agreed generally that non-symbiotic bacteria fix lesser amount of nitrogen than the root nodule bacteria (rhizobia) (James and Olivares, 1997). In spite of their low fixing capacity, some PGPR have shown to be very effective in augmenting this process by making the scares essential nutrient (nitrogen) available to plants.

In non-symbiotic nitrogen fixation process, free living diazotrophs perform their role by stimulating the growth of non- leguminous plants. The genera identified in this group include *Azoarcus*, *Azotobacter*, *Acetobacter*, *Azospirillum*, *Burkholderia*, *Diazotrophicus*, *Enterobacter*, cyanobacteria, *Pseudomonas* and *Gluconacetobacter*(*Anabaena*, *Nostoc*) (Bhattacharyya and Jha, 2012; Vessey, 2003). While in symbiotic form, bacteria such as *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, and *Mesorhizobium* interact with leguminous plants, *Frankia* (a nitrogen fixing Actinomycete),trees and shrubs (Zahran, 2001) in exerting their function. The inoculation of several cultures with diazotroph PGPR (non-symbiotic nitrogen fixing organisms) especially *Azotobacter* and *Azospirillum* has improve the yield of annual and perennial grasses (Tilak et al, 2005). Additionally, Cyanobacterial nitrogen fixation has been essential in the cultivation of rice by increasing the rice-field fertility. *Azotobacter* inoculant on its own also encourage high yield of wheat by over 30% (Gholami et al., 2009).

The initiation of molecular dialogue between host plants and soil bacteria occurs through the release of signal in the form of communication chemicals such as flavonoid (Figure 1)(Perret et al. 2000; Spaink 2000). This molecule encourages plants-microbe relationship. Barriuso et al. (2008) observed that this chemical aid in selection of most compactable partner for their growth and subsequent elimination of suspected harmful once. The communication signal is perceived by a specific bacteria receptor (NodD) and acts as a transcriptional activator of other nodulation genes (nodA, nodB, nodC and nodFE) (Franche *et al*., 2009). The Nod factor acts as an activating agent of root nodule formation of the plant by initiating developmental activities leading to the formation of nodules and residence of rhizobia there in (Long 2001; Gage 2004).

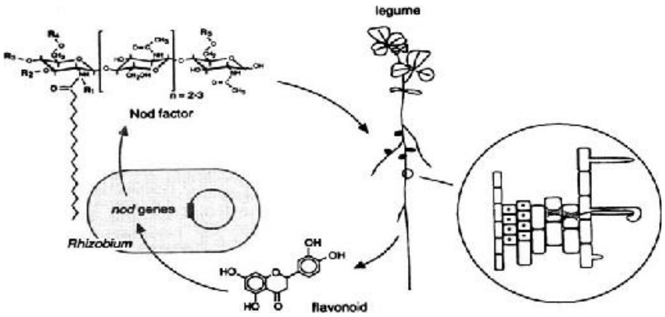

Figure 1: Signal exchange in Rhizobium-plant symbiosis (Schultze and Kondorosi 1998).

Phosphate solubilization

Phosphate is next to nitrogen in the list of essential minerals mostly required by plants. However, there deficiency in soil limit plant growth (Nisha et al., 2014) in a number of ways. It's an insoluble inorganic element which increase the economic viability of any agricultural product when solubilized. The organic forms are found mostly in humus and decayed organic materials. Phosphate represent about 0.2% of plant dry weight as it is essential constituent of nucleic acids, phytin and phospholipids. Additionally, it plays a key role in photosynthesis, respiration, storage and transfer of energy cell division and elongation (Sagervanshi et al., 2012).A large portion of soluble inorganic P is applied to the soil as fertilizer. Due to its rapid rate of fixation and complex formation with other soil elements, it is speedily immobilized and become unavailable to plants (Iordanis et al., 2013; Vikram and Hamzehzarghani, 2008). Organic materials constitute an important reservoir of immobilized phosphate, accounting for about 20-80% of total soil phosphorus. The greater proportion of insoluble inorganic phosphate (apatite) or insoluble organic phosphates (inositol phosphate, phosphomonesters and phosphotriesters) are inaccessible by plant (Pérez-Montano et al., 2014; Iordanis et al., 2013; Khan et al., 2007).

Microorganisms auspiciously has been identified to play an important role in mediating phosphorus available to plants through their participation in the soil phosphorus cycle. These organisms (PGPRs) either directly solubilize and mineralize inorganic phosphorus or facilitate the mobility of the organic form through biogeochemical cycle for more efficient root uptake (Richardson and Simpson, 2011). Specifically, Phosphate Solubilizing Bacteria (PSB) are *Arthrobacter*, *Pseudomonas*, *Alcaligenes*, *Bacillus*, *Burkholderia*, *Serratia*, *Enterobacter*, *Acinetobacter*, *Azospirillum*, *Azotobacter*, *Flavobacterium*, *Rhizobium*, and *Erwinia* (Zaidi et al., 2009). Explicitly, each genus act independently to facilitate the dissolution and uptake of phosphate via *in vitro* condition or other mechanisms (Ramachandran et al., 2007).The PSBs secrete different types of organic acids e.g., carboxylic acid, formic acid, propionic acid, lactic acid, glycolytic acid, fumaric and succinic acid (Vazquez et al., 2000). Kaur et al., (2016) in their discovery established that these organic acids lowers the pH in the rhizosphere, thus causing release of the bound forms of phosphate like Ca_3 $(PO4)_2$ in the calcareous soils. Apart from creating the availability of accumulated phosphate,phosphorus biofertilization also help in increasing the efficiency of biological nitrogen fixation and render availability of Fe, Zn, etc., through production of plant growth promoting substances. PSB are also able to mineralize the insoluble organic phosphate through the excretion of extracellular enzymes such as phytases and C-P lyases phosphatases (Weyens et al., 2010). Authors have reported increase yield of maize (*Zea maize*) (Yazdani et al., 2009), alfalfa (Medicago *sativa* L.) (Rodríguez and Fraga, 1999) and soybean (*Glyxin max*) (Abd-Alla, 2001) by PSB inoculation either when applied singly or in combination of other rhizobacteria (Mahdi *et al.*, 2010; Ahemad and Khan, 2011).

Siderophore production

Iron is a vital element needed by all forms of life. It one of the most abundant mineral deposit on earth. The unavailability of this element in it biological form for plant utilization create perplexing circumstances for it growth. Siderophore which literally means iron carrier or iron chelating is an important strategy developed to increase iron (Fe^{3+}) bioavailability as a unique constituent of cytochrome, enzymes co-factor and heme or non-heme proteins. Siderophores are low molecular weight biomolecules produced by microorganisms, and has strong affinity with Fe^{3+} ions while moving into the cell (Sureshbabu at al., 2016; Neilands, 1989).When Fe is limited, microbial siderophores scavenge and provide plants with Fe from the mineral phase through the formation of soluble Fe^{3+}complexes. Suppression of soil borne plant pathogens by siderophore producing *Pseudomona*s has been reported (Buysens *et al*., 1996; Loper, 1988). Related study has shown that siderophore production occurs in both gram positive and gram negative organisms with specific example of *Bacillus*, *Rhodococcus*,*Pseudomonas* and *Enterobacter* genera (Tian et al., 2009). Consequently, this property is also exhibited by some plant especially grasses (phyto-siderophores) (Van der Helm and Winkelmann, 1994), as they formc onstituent in fertilizer formulation, regulate iron intake capacity in plants and facilitate growth (Miller and Malouin, 1994).

One of the major challenges limiting efficient production of siderophore is environmental factor. These include pH, soil level of iron and their forms, presence of other trace elements, inadequate supply of carbon, nitrogen and phosphorus (Duffy and Défago, 1999). However, siderophore mediated growth promoting activity of PGPR is associated with the suppression of root pathogens by competitive exclusion, hindering deleterious microorganisms access to environmental iron by extracellular siderophores complex formation (Podile and Kishore, 2006; Ahemad and Khan, 2011; Saharan and Nehra, 2011). Elsewhere, works have shown that PGPR synthesis of siderophore improve not only the growth performance of plants and their adaptation in stress environment, but also enhance their ability to absorb both radioactive iron and rhizospheric metals iron even at low concentration (Dimkpa et al., 2009; Robin et al., 2008).

Apart from creating favourable competitive room for bacteria against some pathogenic microorganisms by removing iron from the environment (O´ Sullivan and O´Gara 1992; Persello-Cartieaux *et al.* 2003), chelated iron have also proven to poses one of the weakest affinity with fungi (Loper, and Henkels. 1999). This condition seems possible considering the fact that many bacterial siderophores differ in their strength or abilities to sequester iron leading to it biological and/or adaptive deprivation of the scares commodity (iron) to the pathogenic organisms. Generally, production of siderophore by PGPR is most efficient in controlling the plant root pathogens (Diaz *et al.*, 2002; and Dey *et al.*, 2004).Siderophores has also been linked with potential of promoting bacterial auxin synthesis by reducing the detrimental effects of heavy metals through chelation mechanism (Dimkpa *et al*., 2008).

BIOSTIMULANTS

These are organic chemical compounds that influence plant growth. They are in other words called plant growth regulator or phytostimulant e.g.;Auxin (indole-3-acetic acid (IAA), Gibberellic acid (GA), cytokinins, and ethylene. These chemicalmolecules are recognized over the years as four major plant hormones needed for biochemical, physiological and morphological development. PGPR species belonging to the genera *Azospirillum*, *Pseudomonas*, *Xanthomonas*, *Rhizobium*, *Bradyrhizobium*, *Alcaligenes*, *Enterobacter*, *Acetobacter* and *Klebsiella*, and also the species of *Bacillus pumilus*, *B. licheniformis*, *Paenibacillus polymyxa*, *Phosphobacteria* sp, *Glucanoacetobacter* sp, *Aspergillus* sp and *Penicillium niger* possess the ability to produce phytohormones(Iordanis et al., 2013; Shobha and Kumudini, 2012).

Auxin

Auxin is an essential molecules that regulate directly or indirectly most plant processes. Being the first phytohormone discovered by Darwin (1880) using *Phalaris canariensis* seeds, it has since paved way for more discovery leading to identification ofindole-3-acetic acid (IAA) as the most active and famous plant hormones of auxin group. Irrespective of plant being able to synthesis this chemical molecule (endogenous supply), they still depend largely on external supply (exogenous) for their optimum performance. This exterior meet up is predominantly oversee by PGPR and it associate soil bacterial (Khalid et al., 2006; Patten and Glick, 2002). Auxin triggers a number of cellular function ranging from differentiation of vascular tissues, initiation of lateral and adventitious roots, stimulation of cell division, elongation of stems and roots, and orientation of root and shoot growth in response to light and gravity (Glick, 1995). For PGPR to produce IAA more efficiently, consideration of the type of specie and strain, it culture condition, developmental stage cum availability of nutrient in the rhizosphere are of important (Ashrafuzzaman et al., 2009).

Although other auxins, such as indole 3 butyric acid (IBA) and phenyl acetic acid (PAA) have also been identified in plants (Normanly, 1997), scientist are yet to understand their complexity and most importantly their mode of action. Contrary, bacteria IAA producers (BIPs)are found to be most abundant in the soil/plant auxin pool and L-Tryptophan (L-TRP) as a precursor that aid in the increase and production of auxin. This was demonstrated in *Bacillus amyloliquefaciens* FZB42 (Idris *et al.*, 2007), *Fluorescent Pseudomonas* (Karnwal, 2009) and *Azotobacter* and *Azospirillum* strains in canola plant (Yasari and Patwardhan, 2007). Findings suggest that rising level of L-Tryptophan increases the biochemical and metabolic activities of BIPs or auxin producing bacterial (APBs), with a corresponding response in root length and modifications of root architecture. The four main metabolic pathways dependent of tryptophan are; tryptophol, ryptamine, indole-3-pyruvic acid and indole-3-acetamide pathway (Bartel, 1997). Emerging evidence illustrate that organisms which produces low quantity of auxins as a result of absence of L-Tryptophan have the propensity of turning up high amount of auxins when augmented with L-tryptophan, especially in the presence of viable strain of *Rhizobium*(Zahir et al. 2010; Zahir et al., 2004). Importantly, it interesting to note that the indigenous auxin (IAA) produced by plant though will contribute to plant growth, it might still not be necessarily enough for the optimal performance of the plant (Pilet and Saugy, l987). Hence, justifying the exogenous need (IAA produced by PGPR) of this chemical messenger to bring to the peak, plant growth, development and adaption to stressed environment.

Gibberellic Acid (GA)

The exact mechanisms by which PGPR promote plant growth via the synthesis of gibberellic acid are still not yet fully understood. It general thought has remain that, GA promote the development of stem tissue, root elongation and lateral root extension (Yaxley*et al.*, 2001). GA constitute a group of tetracyclic diterpenes that greatly influence the processes of seed germination, leaf expansion, stem elongation, fruit development, flower and trichome initiation (Yamaguchi 2008). Because of their vital role in improving efficient photosynthetic processes in plants, gibberellins and it producing genera remain the primary target during environmental stress condition, making it an important plant growth bioregulator that can increase the stress tolerance of many crop plants. The improvement of plant growth by some rhizobacteria (PGPR) producing gibberellins was reported (Kang et al., 2009). The exogenous application of this growth hormones may be useful in amendment of polluted soil and improvement of crop performance (Iqbal et al. 2011). Application of GA has shown to increase considerably the grain yield in wheat (Iqbal et al. 2011; Radi et al. (2006), barley (Vettakkorumakankav 1999) and tomato by decreasing stomatal resistance and improved water use efficiency (Maggio et al., 2010). Conclusively, gibberellin is involve in plant morphology modification and stimulate the development of aerial part (Van Loon, 2007) as they remain an excellent alternative for inducing stress tolerant.

Cytokinins

Cytokinin play a significant role during cell division, vascular differentiation nutrient mobilization, chloroplast biogenesis, shoot differentiation, leaf senescence, apical dominance, anthocyanin production, and photomorphogenic development (Davies, 2004). It participate also in vascular cambium sensitivity, proliferation of root hairs and contrarily in inhibition of lateral root formation and primary root elongation (Aloni et al., 2006). This molecule can be acquired endogenously and exogenously by either plant or PGPR respectively. Plant increase uptake of endogenous cytokinin via the promotion of biosynthesis (Pospíšilová 2003b). Studies has shown that during plant growth, cytokinin perfectly regulate plant adaptation especially in salt polluted site (Hadiarto and Tran 2011). Biochemical processes revealed that cytokinin serve as a major antagonist to abscisic acid (ABA), thus resulting in metabolic alteration of other phytohormones (Pospíšilová 2003a). During water scarcity, the plant cytokinin content reduce drastically with a resultant positive increase in ABA concentration. Assessing the production of plant hormones by different *Streptomyces* strains in broth medium, shows that all strains synthesized cytokinins and gibberellins (Mansour et al., 1994). Though this is vital for phyto development, it mechanism of action is still not well elucidated. Cytokinin receptor gene of most plants and organisms are regulated by changes in osmotic conditions and as well demonstrate a complex osmotic stress response (Merchan et al., 2007).Research has shown that inoculating seedling with cytokinin producing strains of *Bacillus subtilis* confer the plants resistance against environmental stress.

Ethylene

This is a unique phyohormone with wide range of biological activities. The beneficial role of this biomolecule is best recorded at low concentration. It hinders some key developmental properties e.g., root elongation, induce defoliation and other cellular processes at high concentration resulting to reduced crop performance (Bhattacharyya and Jha, 2012). Pierik, *et al.* (2006) was of the opinion that it classification as a senescence hormone was due to it inhibitory role to plant growth. To overcome this alarming consequences, an enzyme 1-aminocyclopropane-1 carboxylic acid (ACC) deaminase is needed. The role of this biocatalyst is to degrade the plant ACC which is the direct precursor of ethylene synthesis in plant to α- ketobutyrate and ammonium (Glick et al., 2007). The result of the degradation is the reduction of plant ethylene production through a range of mechanisms, while the PGPR producing ACC-deaminase regulates the ethylene level in plant and prevents the growth inhibition caused by high levels of ethylene (Noumavo et al., 2016). PGPR capable of inducing exogenous production of ethylene via degradation of the endogenous product using enzyme include *Acinetobacter, Achromobacter, Agrobacterium, Alcaligenes, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Ralstonia, Serratia* and *Rhizobium.* Work have shown that PGPR ACC deaminase activities was vital for *Brassica napus* growth (Dell'Amico et al., 2008). Pierik et al., (2006) suggested that at low concentration of ethylene mediated by PGPR, the plant yield, growth performance and germination properties of

Arabidopsis thaliana get accelerated. However, this vaporous hormone regulate also root initiation, fruit ripening, seed germination, leaf abscission and wilting (Kaur et al.,2016).

BIOCONTROL

PGPR has been identified as biocontrol agent with capacity to suppress a wide range of organisms possible of presenting disease condition to plant. For PGPR to be an efficient biocontrol agent against pathogenic bacteria, fungi and viruses, it must utilize one of the following mechanisms; production of antibiotics, competition for nutrients and niche, signal interference, induced systemic resistance, hydrogen cyanide and lytic enzymes production. (Podile and Kishore, 2006; Lugtenberg and Kamilova, 2009). Generally, these mode of actions are classified as either direct or indirect form of antagonism, with fungi, bacteria and nematode being the most pathogenic organisms of interest in their order of severity. Consequently, this means of plant disease control involves application of beneficial rhizobacteria or their metabolites in minimizing/neutralizing the negative impact of pathogens while promoting healthy living in plants (Junaid et al. 2013).

Antibiotics Production

Antibiotics production is one of the most studied biocontrol strategies display by PGPR. A good example include amphisin, 2,4-diacetylphloroglucinol (DAPG) oomycin-A, phenazine, pyoluteorin, pyrrolnitrin, tensin, tropolone, and the cyclic lipopeptides (Loper and Gross, 2007) synthesis. Others include oligomycin A, kanosamine, zwittermicin A, and xanthobaccin (Compant, *et al.*, 2005).Basically, these biochemical are produced by *Pseudomonas* strains. *Bacillus*, *Streptomyces*, and *Stenotrophomonas* sp. As an active chemical agent, they are influenced by biotic and abiotic factor and environmental stress. Antibiotics are low weight molecular compound that suppress the development of plants pathogenic microorganisms. Phloroglucinols (Phl), 2-hexyl-5-propyl resorcinol (HPR), D-gluconic acid, hydrogen cyanide (HCN) and 2-hydroxymethyl-chroman-4-one have successfully been utilized as biocontrol agent (Perneel et al. 2008; Kang et al. 2004; Kaur et al. 2006; Cazorla et al. 2006).Elsewhere, increase productivity as a result of biocontrol inoculant was reported in *S. rochei* inhibition of pepper root rot caused by phytopthora (Ezziyyani *et al.*, 2007); *S. platensis* against *R. solani* leaf blight/seedling blight of rice (Wan *et al.*, 2008); Fusarium root rot and tomato wilt caused by *S. griseoviridis* (Minuto *et al.*, 2006); *S. hygroscopicus* infection of*Colletotrichum gloeosprioides* anthacnose and in wide range of crops (Prapagdee *et al.*, 2008)

Nutrients and niche competition

For rhizospheric bacteria to claim dormant over the rest of soil microorganisms, it must be able to compete favourably for the available nutrient and space. This is a vital strategy needed to limit the incidence and severity of plant disease (Kamilova et al. 2005). Consequently, this adaptation makes the root unfit to host phytopathogens as a result of PGPR rapid and abundant colonization. As a negative form of association, the most competent group of microorganisms takes charge and control the whole metabolic activities. Aside the inherent growth which PGPR acquires via competition as a result of sufficient nutrient availability, other properties such as presence of flagellium, lipopolysaccharide, chemotaxis and the usage of secreted root exudate enhanced their survival (Lugtenberg and Kamilova, 2009). A good illustration can be seen in unavailability of iron to phytopathogenic fungi when chelated by siderophores synthesized by PGPR. Conversely, iron is one of the essential nutrients required by all microorganisms for synthesis of ATP, formation of heme, reduction of ribotide precursors of DNA, and a number of functions (Saraf et al. 2011). In niche competition, a physical occupation of site by PGPR is enhanced through delay tactics, by preventing the colonization of pathogens until the available substrate is exhausted (Heydari and Pessarakli 2010). This feature has been an age long adaptive property exerted by beneficial soil microorganisms to occupy the root rhizosphere and make available scarce nutrient for their upkeep (Lugtenberg et al. 2001).

Induced Systemic Resistance (ISR)

PGPR trigger inducement of some kind of defense system that is capable of fighting some pathogenic bacteria, fungi and viruses. This potentially positions the plant as a much stronger and highly adapted specie (Van Loon, 2007). The gene and gene product involve in this form of biological control phenomenon has not been well documented. Unlike the systemic acquired resistance (SAR) (Handelsman and Stabb 1996), which is a stateof defense that is activated all through the plant following the primary infection by pathogens (Ryals et al. 1996), Induce systemic resistance (ISR) utilize organic acid and plant hormones (salicylic acid, jasmonic acid, and ethylene) in plants signaling and stimulation of the host plant defense response against variety of plant pathogens (Niranjan et al. 2005; Beneduzi et al. 2012; Pieterse et al. 2014). PGPR response to ISR is usually felt by increased physical and mechanical strength of the cell wall as well as adjusting their physical and biochemical reaction to environmental stress (Labuschagne et al. 2010).ISR in PGPR can be in the form of salicylic acid, siderophores production, lipopolysaccharide, flagella, N-acyl homoserine lactone (AHL) molecules (Van Loon 2007; Shuhegger et al. 2006) and antibiotics. The participating organisms in this form of biocontrol include *Bacillus pumilus*, *Pseudomonas sp* and enterobacteria (Jourdan et al., 2009). In a wider scale, application of PGPR strain as seed coat have improved tremendously the ISR against *Colletotrichum lagenarium* which causes anthracnose in cucumber, *Pseudomonas syringae* causing angular leaf spot and bacterial wilt by *Erwinia tracheiphila* (Zehnder et al. 2001).

Signal Interference

For an organism (beneficial or pathogenic) to exert it function, a particular number or quorum is required. This requirement especially in gram negative organisms is communicated via a small diffusible signaling molecule called N-acyl homoserine lactone (AHL). This regulatory agent allow the cells to sense the population of their kind and to express certain character. The development of essential physiological characters such as production of pathogenicity/virulence factors, swarming, swimming and twitching motilities, rhizosphere colonization can also be credited to cell signaling (Gray and Garey 2001; Miller and Bassler 2001). The discovery of enzyme capable of degrading AHL is considered to be a fight in the right direction against phytopathogens quorum-sensing system, as *Bacillus thuringiensis* has shown to efficiently decrease the incidence and development of potato soft rot caused by *E. carotovora* using signal inference strategy (Dong et al. 2004).

Lytic enzymes production

The production of extracellular enzymes such as chitinases, ß-1-3 glucanases, lipases, cellulases, and proteases by rhizobacteria has been suggested to be a vital form of biocontrol (Markowich and Kononova 2003). They are hydrolytic enzymes that are capable of degrading wide range of compound usually of plant origin. For plants to be hydrolyzed, chitinases, glucanases, cellulases, proteases, dehydrogenases, lipases, phosphatases, exo and endo-polygalacturonases, pectinolyases must be secreted (Joshi et al., 2012; Whipps, 2001), more so for the lysing of fungal cell wall(Mabood et al. 2014). Palumbo et al. (2005) has suggested the significant of beta-1, 3-glucanase on the biocontrol activities of *Lysobacter enzymogenes* strain C3 against Bipolaris leaf spot caused by *Phytium* sp. This innate properties shield the plants from the attack of foreign pathogens. As multifunctional organic protein, these enzymes form protection from desiccation and against abiotic and environmental stress (Qurashi and Sabri, 2012). Lytic enzyme can be used in the control of blight in pepper by *Phytophthora capsici*(Jung et al. 2005), Fusarium infection (Hariprasad et al. 2011) and sugar beet by *Pythium ultimum* (Dunne et al., 1997). Chaiharn *et al.*, (2008)illustrate the antagonistic potential of PGPR by production of chitinase, β 1, 3 glucanase, proteolytic enzymes and cellulase at low concentration, even as *Pseudomonas* sp has proven to be a good candidate in the synthesis of lytic enzymes (Cattelan *et al.*, 1999). Mycoparasitic and Trichoderma species have also been implicated in its antagonistic biocontrol activities against R. necatrix and other plant pathogens using chitinases (Hoopen and Krauss 2006; Harman et al. 2004).

Hydrogen cyanide (HCN)

Production of hydrogen cyanide (cyanogenesis) is predominantly associated to *pseudomonas* sp quantitatively, this can be detected according to the techniques described by Lorck (1948). HCN a well studies biocontrol agent is known to be a volatile compound. Its cyanide ion inhibits most metalloenzymes, especially copper containing cytochrome c oxidases (Blumer and Haas 2000). Cyanide produced by *Pseudomonas* strains has successfully been used to curb canker of tomato (Lanteigne et al., 2012).As a secondary metabolite produced by gram negative bacteria, it is formed from glycine and catalyzed by HCN synthase (Castric, 1994). *P. fuorescens* strain CHA0 (Voisard *et al.*, 1989) was used to control tobacco black root rot caused by *Thielaviopsis basicola* (Laville *et al*., 1998). However, because of the aggressive colonizing strength of *Fluorescent pseudomonas*, it has effectively been used in the control of soil-born plant pathogens (Lugtenberg et al. 2001). There are still indications that a good number of rhizobacteria are cyanogenic when provided with glycine in their culture medium.

Role of PGPR in Phytoremediation

As soil constantly welcome large inflow of waste and contaminated material, they overtime have stern impact on the environment and human health. Most common of these pollutants are heavy metals (Hg, Pb, Cr, Co, Zn, Ni and Cd). They have been attributed to industrialization, urbanization and civilization. In agricultural development, soil pollution has implicated human activities such as excessive fertilizer application, indiscriminate disposal of sewage and municipal waste, and pesticides/insecticide usage. Though at immediate these agro chemicals facilitate growth and productivity and leave records of metal residues that impair plant growth and microbial metabolism. Because they are non-biodegradable, it remediation becomes extremely difficult and can only be transform from one state to another. Soil rhizobacteria assisted phytoremediation has become an alternative of choice in detoxifying sites because it's cost effective, ecofriendly and aesthetic. Decontaminating these heavy metal polluted soil occur through chelation, solubilization, and mineralization using large consortium of soil microorganisms residence in the rhizosphere, thus aiding their bioavailability/mobility and bioaccumulation by plants.

Commercialization of PGPR and African challenge

Despite the knowledge gap of PGPR by agriculturists in the developing and less developed world, a good number of bacteria has long been used (Banerjee et al., 2006) for agro practices in advance countries and emerging economy like China and India. Although it benefit is so enormous, it still represent an infinite proportion of the world commercial agricultural development. Some of the PGPR strains that have gain much attention in recent time include; *Agrobacterium radiobacter*, *Azospirilium lipoferum*, *Bacillus licheniformis*, *Bacillus subtillis*, *Burkholderia cepacia*, *Pseudomonas chlororaphis*, *Streptomyces lydicus*, *Pseudomonas syringae*, *Pseudomonas fluorescens* and *Bacillus pumilus* (Glick, 2012). Effective and efficient utilization of this biotechnology for aggressive food production in the wake of rising human population is paramount. More in situ research base approach should be carried out to ascertain the most suitable strain and appropriate biotic condition needed for growth, while also paying good attention on the soil quality/property and season of their optimum performance. There is need for government agency in the tropics to have a uniform policy and regulation regarding strain of organisms to be released into the environment (Glick, 2012), and their stake on genetically modified organisms. More work still need to be done in the developing world to commercialize agriculture (industrial agriculture) that has for decades been left in the hands of peasant farmers who is ill equipped with modern obtainable practice. Secondly, with the dwindling economy as a result of fall in oil price, agriculture still remain a lifelong viable revenue for government, as more research need to be done for strain-crop specificity and indebt soil analysis while considering African climatic condition. Thirdly there is need for proper campaign and education of her populace on genetically modified organisms and importance of microbial or PGPR inoculant agro base practices.

Conclusion

In the past century, for an agricultural practice to the successful one must not neglect the use of chemical fertilizer, herbicides and pesticides. Initially, they aid in plant growth while at a long run exert their negative effect. This norm has not only affected the soil and it inhabitant but also renders threat to human life through the food chain. With rise in soil pollution, climatic condition, soil-born pathogen and extensive land overuse, the soil has become grossly infertile and unproductive. As evident in the low agro output, food insecurity couple with rising human population. To achieve self-sufficiency, effort must be made especially in the tropics to key into scientific knowledge through broad understanding of soil-plant-microbial interaction and their mechanism of action. This will not only lead to bumper harvest but keep the soil safe and healthy. Although, the campaign for the use of PGPR has been on for decades, it has not been embraced in Africa, due to poor understanding and lack of government policy. However, actions should focus on substituting agrochemicals with bioproduct such as biofertilizer, bioinsecticide and bioherbicide with consortium of beneficial PGPR. Highlighted advantages of these bioinoculant in terms of increased plant nutrient, and biocontrol through, induction of systemic resistance and nutrients or space competition must be carefully stated and comprehended by farmers to enhance crop yield while retaining soil quality. Keying into this process via genetic engineering of PGPR as an integral constituent in modern food production will mitigate soil pollution, ecosystem alteration, and destruction of soil flora and fauna. Finally, there is need to harness and enforce this technology especially in the developing world to curtail the possible humanitarian crisis (famine) in areas ravage by war and terrorism to boost food production and improve the eco environmental safety of our community.

References

Abd-Alla, M.H. 2001. Regulation of nodule formation in soybean-Bradyrhizobium symbiosis is controlled by shoot or/and root signals. J. Plant. Growth. Regul. 34:241-250.

Adesemoye, A.O., Torbert. H.A. and Kloepper J.W. 2008. Enhanced plant nutrient use efficiency with PGPR and AMF in an integrated nutrient management system. Can. J. Microbiol. 54:876-886 doi:10.1139/W08-081

Afzal, and Asghari. 2008 Rhizobium and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat. Int. J. Agri. Biol. 10 (1): 85-88doi: 07-092/MFA/2008/10–1–85–88 http://www.fspublishers.org

Ahemad, M. and Khan, M.S. 2011. Functional Aspects of Plant Growth Promoting Rhizobacteria: Recent Advancements. Microbiol. Insights 1 (3): 39-54 doi: 10.5567/IMICRO-IK.2011.39.54

Ahmad, F., Ahmad, I. and Khan, M.S. 2008. Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. Microbiol. Res.163(2):173-181PMID:16735107 doi:10.1016/j.micres.2006.04.001

Alalaoui, A.C.2007. Fertilisation minérale des cultures: les éléments fertilisants majeurs (Azote, Potassium et Phosphore). Bull Mens Inform Liaison 155:1-4.

Aloni, R., Aloni, E., Langhans, M. andUllrich, C.I.2006. Role of cytokinin and auxin in shaping root architecture: Regulating vascular differentiation, lateral root initiation, root apical dominance and root gravitropism. Ann. Bot. 97(5): 883-893.doi:10.1093/aob/mcl027 PMC2803412

Anjum, M.A., Sajjad, M.R., Akhtar, N., Qureshi, M.A., Iqbal, A., Jami, A.R. and Hasan M. 2007. Response of cotton to plant growth promoting rhizobacteria (PGPR) inoculation under different levels of nitrogen. J. Agri. Res. 45 (2):135-143.

Antoun, H., Beauchamp, C.J., Goussard, N., Chabot, R. and Llande, R. 2004. Potential of *Rhizobium* and *Bradyrhizobioum* species as plant growth promoting rhizobacteria on non-legumes: effect on radishes. Plant Soil. 204:57-67

Arora, N.K, Khare, E., Oh, J.H., Kang, S.C. and Maheshwari, D.K. 2008 Diverse mechanisms adopted by fluorescent Pseudomonas PGC2 during the inhibition of Rhizoctonia solani and Phytopthora capsisi. World. J. Microbiol. Biotech. 24(2):581-585 doi:10.1007/s11274-007-9505-5

Arora, N.K., Tewari, S., Singh, S., Lal, N. and Maheshwari, D.K. 2012 PGPR for protection of plant health under saline conditions. In: D.K. Maheshwari, (ed.) Bacteria in agrobiology: Stress Manag. pp. 239-258 doi: 10.1007/978-3-662-45795-5_12 ·

Arshad, M. and Frankenberger, W.T. 1992 “Soil Microbial Ecology,” In: F. B. Metting, Ed., Microbial Production of Plant Growth Regulators, Marcel Dekker, Inc., New York.

Ashrafuzzaman, M., Hossen, F.A., Ismail, M.R., Hoque, M.A., Islam, Z.M., Shahidullah, S.M. and Meon, S. 2009. Efficiency of plant growth-promoting rhizobacteria (PGPR) for the enhancement of rice growth. Afr. J. Biotech 8 (7):1247-1252.

Babalola, O.O. and Akindolire, A.M. 2011. Identification of native rhizobacteria peculiar to selected food crops in Mmabatho municipality of South Africa. Biol. Agric. Hort. 27(3-4):294-309doi.org/10.1080/01448765.2011.647798

Barriuso, J., RamosSolano, B., Fray, R.G., Cámara, M., Hartmann, A. and Gutiérrez Mañero, F.J. 2008. Transgenic tomato plants alter quorum sensing in plant growth–promoting rhizobacteria. Plant Biotech. J. 6 (5): 442-452.doi: 10.1111/j.1467-7652.2008.00331.x

Bartel, B. 1997. Auxin biosynthesis. Annu. Rev. Plant Physiol. Plant Mol. Biol. 48:51-66. PMID: 15012256 doi: 10.1146/annurev.arplant.48.1.51

Bashan, Y. and Levanony, H. 1990. Current status of *Azospirillum* inoculation technology: *Azospirillum* as a challenge for agriculture. Can. J. Microbiol. 36 (9): 591-608.doi: 10.1139/m90-105

Belimov, A.A. and Dietz, K.J. 2000. Effect of associative bacteria on element composition of barley seedlings grown in solution culture at toxic cadmium concentrations. Microbiol. Res. 155 (2):113-121.PMID: 10950194

Beneduzi, A., Ambrosini, A. andPassaglia,L.M.P. 2012. Plant growth-promoting rhizobacteria (PGPR): Their Potential as antagonists and biocontrol agents. Genet. Mol. Biol.35 (4): 1044-1051.PMCID: PMC3571425

Bhardwaj, D., Ansari, M.W., Sahoo, R.K. and Tuteja, N. 2014. Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microb.Cell. Fact.13, 66.PMCID: PMC4022417 doi: 10.1186/1475-2859-13-66

Bhattacharyya, P.N. and Jha, D.K. 2012. Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World. J. Microbiol. Biotech.28 (4):

1327-1350. PMID: 22805914 doi: 10.1007/s11274-011-0979-9

Blumer, C. and Haas, D. 2000. Mechanisms, regulation and ecological role of bacterial cyanide byiosynthesis. Arch. Microbiol. 173 (3):170-177PMID: 10763748

Boraste, A., Vamsi, K.K., Jhadav, A., Khairnar, Y., Gupta, N., Trivedi, S., Patil, P., Gupta, G., Gupta, M., Mujapara, A.K. and Joshi B. 2009.Biofertilizers: A novel tool for agriculture. Int. J. Microbiol. Res. 1(2): 23-31. ISSN: 0975-5276

Bowen, G.D. andRovira, A.D. 1999. The rhizosphere and its management to improve plant growth. Adv. J.Agron. 66:1-102.

Broeckling, C.D., Broz, A.K., Bergelson,J., Manter, D.K. and Vivanco, J.M. 2008. Root exudates regulate soil fungal community composition and diversity. Appl. Environ. Microbiol.74 (3):738-744. doi: 10.1128/AEM.02188-07

Burd, G.I., Dixon, D.G. and Glick, B.R. 2000. Plant growth promoting bacteria that decrease heavy metal toxicity in plants. Can. J. Microbiol. 46 (3):237-245. PMID: 10749537

Buysens, S., Heungens, K., Poppe, J. and Hofte, M. 1996. Involvement of pyochelin and pyoverdin in suppression of *Pythium*-induced damping-off of tomato by *Pseudomonas aeruginosa*7NSK2. Appl. Environ. Microbiol. 62 (3): 865-871. PMID: 16535275

Cakmakci, R., Donmez, F., Aydm, A.and Sahin, F. 2006. Growth promotion of plants by plant growth promoting rhizobacteria under greenhouse and two different field soil conditions. Soil. Biol. Biochem. 38:1482-1487

Cakmakci, R., Erat, M., Erdogan, U. and Donmez, M.F. 2007. The influence of plant-growth-promoting rhizobacteria on growth and enzyme activities in wheat and spinach plants. J. Plant. Nutrit. Soil. Sci. 170:288-295.

Castric, P. 1994. Influence of oxygen on the *Pseudomonas aeruginosa* hydrogen cyanide synthase. Curr. Microbiol. 29 (1):19-21.doi:10.1007/BF01570186

Cattelan, M.E., Hartel, P.G. and Uhrmann, J.J. 1999. Screening of plant growth promoting rhizobacteria to promote early soybean growth. SoilScience Society of American Journal. 63:1670-1680.

Cazorla, F.M., Duckett, S.B., Bergstr€om, E.T., Noreen, S., Odijk, R., Lugtenberg, B.J.J., Thomas-Oates. J. and Bloemberg, G.V. 2006. Biocontrol of avocado dematophora root rot by antagonistic *Pseudomonas fluorescens* PCL1606 correlates with the production of 2-hexyl 5-propyl resorcinol. Mol. Plant. Microbe. Interact. 19:418-428

CFS (2012). Committee on world food security, final report 39, 15–20 October, Rome Italy. http://www.fao.org/fileadmin/user_upload/bodies/CFS_sessions/39th_Session/39emerg/MF027_CFS_39_FINAL_REPORT_compiled_E.pdf

Chaiharn, M., Chunhaleuchanon, S., Kozo, A. and Lumyong, S. 2008. Screening of rhizobacteria for their plant growth promoting activities. *Kmitl Sci. Tech*. 8.

Compant, S., Clément, C. and Sessitsch, A. 2010. Plant growth promoting bacteria in the rhizo and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. Soil Biol. Biochem. 42:669-678.

Compant, S., Duffy, B., Nowak, J., Clément, C. and Barka, E.A. 2005. Use of plant growth-promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action, and future prospects. Appl. Environ. Microbiol. 71:4951-4959.

Darwin, F. 1880. Life and Letters of Charles Darwin, ed. F. Darwin, 506 p.

Dastager, S.G., Deepa, C.K. and Pandey, A. 2010. Potential plant growth promoting activity of Serratia nematophila NII- 0.928 on black papper (Piper nigrum L.). World J. Microbiol. Biotechnol. 27:259-265.

Davies, P.J. 2004. Plant hormones: biosynthesis, signal transduction, action. Kluwer Academic Publishers, Dordrecht

Dell'Amico, E., Cavalca, L. and Andreoni, V. 2008. Improvement of Brassica napus growth under cadmium stress by cadmium-resistant rhizobacteria. Soil Biol. Biochem. 40:74-84

Dey, R., Pal, K.K., Bhatt, D.M. and Chauhan, S.M. 2004. Growth promotion and yield enhancement of peanut (*Arachis hypogaea* L.) by application of plant growth promoting rhizobacteria. Microbiol Res. 159: 371-394.

Diaz, M.E., Villa, P. and Frias, A. 2002. Evaluation of the siderophores production by *Pseudomonas aeruginosa* PSS. Revista Latinoamericana de Microbioloogia. 44: 112-117.

Dimkpa, C.O., Merten, D., Svatos, A., Büchel, G. and Kothe, E. 2009. Siderophores mediate reduced and increased uptake of cadmium by *Streptomyces tendae* F4 and sunflower (*Helianthus annuus*), respectively. J. Appl. Microbiol. 107:1687-1696.

Dimkpa, C.O., Svatos, A., Dabrowska, P., Schmidt, A., Boland. W. and Kothe, E. 2008. Involvement of siderophores in the reduction of metal-induced inhibition of auxin synthesis in *Streptomyces* spp. Chemosphere 74:19-25.

Dong, Y.H., Zhang, X.F., Xu, J.L. and Zhang, L.H. 2004. Insecticidal Bacillus thuringiensis silences Erwinia carotovora virulence by a new form of microbial antagonism, signal interference. Appl. Environ. Microbiol. 70:954–960

Duffy, B.K. and Défago, G. 1999. Environmental factors modulating antibiotic and siderophore biosynthesis by *Pseudomonas fluorescens* biocontrol strains. Appl. Environ. Microbiol. 65 (Suppl 6): 2429-2438.

Dunne, C., Crowley, J.J., Moenne-Loccoz, Y., Dowling, D.N., de Bruijn,.F.J. and O'Gara, F. 1997. Biological control of Pythium ultimum by Stenotrophomonas maltophilia W81 is mediated by an extracellular proteolytic activity. Microbiol 143:3921-3931

Egamberdieva, D. and Lugtenberg, B. 2014. Use of Plant Growth-Promoting Rhizobacteria to Alleviate Salinity Stress in Plants. In *Use of Microbes for the Alleviation of Soil Stresses*; Springer: New York, NY, USA, 2014; Volume 1, pp. 73–96.

Ezziyyani, M., Requena, M.E., Egea-Gilabert, C. and Candela, M.E. 2007. Biological control of phytophthora root rots of pepper using *Trichoderma harzianum* and *Streptomyces rochei* in combination. Phytopathology. 155: 342-349.

Foster, R.C. 1988. Microenvironments of soil organisms. Biol. Fertil. Soils 6:189-203.

Franche, C., Lindstrom, K. and Elmerich, C. 2009. Nitrogen-fixing bacteria associated with leguminous and non-leguminous plants. Plant Soil 321: 35-59.

Gage, D.J. 2004. Infection and invasion of roots by symbiotic, nitrogen-fixing rhizobia during nodulation of temperate legumes. Microbiol. Mol. Biol. Rev. 68**:**280-300.

Gholami, A., Shahsavani, S. and Nezarat, S. 2009. The effect of plant growth promoting rhizobacteria (PGPR) on germination, seedling growth and yield of maize. World Acad. Sci. Eng. Technol. 49, 19-24.

Glick. B.R. 2012. Plant Growth-Promoting Bacteria: Mechanisms and Applications. Scientifica Volume 2012 (2012), Article ID 963401, 15 pages.

Glick, B.R., Cheng, Z., Czarny. J. and Duan, J. 2007. Promotion of plant growth by ACC deaminase-producing soil bacteria. Euro. J. Plant. Pathol. 119:329-339.

Glick, B.R., Penrose, D.M. and Li, J.P. 1998. A model for the lowering of plant ethylene concentrations by plant growth-promoting bacteria. J. Theor. Biol. 190:63-68.

Glick, B. 1995. The enhancement of plant growth by free-living bacteria. Can. J. Microbiol. 41, 109-117.

Gray, K.M. and Garey, J.R. 2001. The evolution of bacterial LuxI and LuxR quorum sensing regulators. Microbiol 147:2379-2387

Gyaneshwar, P., Kumar, G.N., Parekh, L.J. and Poole, P.S. 2002. Role of soil microorganisms in improving P nutrition of plants. Plant and Soil. 245: 83-93.

Hadiarto, T. and Tran, L.S. 2011. Progress studies of drought-responsive genes in rice. Plant Cell. Rep. 30:297-310

Haghighi, B.J., Alizadeh, O., Firoozabadi, A.H. 2011. The Role of Plant Growth Promoting Rhizobacteria (PGPR) in Sustainable Agriculture. Adv. Environ. Biol. 5:3079-3083

Handelsman, J. and Stabb, E.V. 1996. Biocontrol of soil-borne plant pathogens. Plant Cell 8: 1855-1869.

Hariprasad, P., Divakara, S.T. and Niranjana, S.R. 2011. Isolation and characterization of chitinolytic rhi- zobacteria for the management of Fusarium wilt in tomato. Crop Prot. 30:1606-1612

Harman, G.E., Howel, C.H., Viterbo, A., Chet, I. and Lorito,M. 2004. Trichoderma species-opportunistic, a virulent plant symbionts. Nat. Rev. Microbiol. 2:43-56

Heydari, A. and Pessarakli, M. 2010. A review on biological control of fungal plant pathogens using microbial antagonists. J. Biol. Sci. 10: 273- 290

Hiltner, L. 1904. Über neuere Erfahrungen und Probleme auf dem Gebiete der Bodenbakteriologie unter besonderer Berücksichtigung der Gründüngung und Brache. *Arb DLG*. 98:59-78.

Hoopen, G.M. and Krauss, U. 2006. Biology and control of Rosellinia bunodes, Rosellinia necatrix and Rosellinia pepo: a review. Crop. Prot. 25:89-107.

Idris, S.E., Iglesias, D.J., Talon, M. and Borriss, R. 2007. Tryptophan-dependent production of Indole-3-Acetic Acid (IAA) affects level of plant growth promotion by *Bacillus amyloliquefaciens* FZB42. Molecular Plant-Microbe Interactions. 20: 619-626.

Iordanis Chatzipavlidis, Io Kefalogianni, Anastassia Venieraki1 and Wilhelm Holzapfel2 (2013). Status and trends of the conservation and sustainable use of microorganisms in agroindustrial processes. Commission on genetic resources for food and agriculture**.**

Iqbal, N., Nazar, R., Iqbal M.R.K., Masood, A., Nafees, A.K. 2011. Role of gibberellins in regulation of source sink relations under optimal and limiting environmental conditions. Curr. Sci. 100:998-1007

Loper, J.E and Gross, H. 2007. Genomic analysis of antifungal metabolite production by *Pseudomonas fluorescens* Pf-5. European Journal of Plant Pathology, 119, 265-278.

Ryals, J.A., Neuenschwander, U.H., Willits, M.G., Molina, A., Steiner, H.Y. and Hunt, M.D. 1996. Systemic acquired resistance Plant Cell. 8(10): 1809-1819.doi: 10.1105/tpc.8.10.1809

Jackson, T. 1999. Renewable energy. Summary paper for the renewable series. Energy policy 20: 861-883.

James, E.K., Olivares, F.L., Baldani, J.L. and Döbereiner, J. 1997. *Herbaspirillum*, an endophytic diazotroph colonizing vascular tissue in leaves of *Sorghum bicolor* L. Mocnch. J Exp Bot 48:785-797

Joshi, Y.B., Chu, J. and Pratico, D. 2012. Stress hormone leads to memory deficits and altered tau phosphorylation in a mouse model of Alzheimer’s disease. J. Alzheimers Dis. 31:167-176.

Jourdan, E., Henry, G., Duby, F., Dommes, J., Barthelemy, J.P., Thonart, P., Ongena, M. 2009. Insights into the defenserelated events occurring in plant cells following perception of surfactin-type lipopeptide from *Bacillus subtilis*. Mol. Plant Microbe Interact. 22:456-468.

Junaid, J.M., Dar, N.A, Bhat, T.A., Bhat, A.H. and Bhat, M.A. 2013. Commercial biocontrol agents and their mechanism of action in the management of plant pathogens. Int. J. Mod. Plant. Ani. Sci. 1:39-57

Jung, W.J., Jin, Y.L., Kim, K.Y., Park, R.D. and Kim, T.H. 2005. Changes in pathogenesis-related proteins in pepper plants with regard to biological control of phytopthora blight with Paenibacillus illinoisensis. Biocontrol 50:165-178

Kamilova, F., Validov, S., Azarova, T., Mulders, I. and Lugtenberg, B. 2005. Enrichment for enhanced competitive plant root tip colonizers selects for a new class of biocontrol bacteria. Environ Microbiol 7:1809-1817

Kang, J.G., Shin, S.Y., Kim, M.J., Bajpai, V., Maheshwari, D.K. and Kang, S.C. 2004. Isolation and anti-fungal activities of 2-Hydroxy-methyl-chroman-4-one produced by Burkholderia sp. MSSP. J. Antibiot. 57(11):726-731

Kang, S., Joo, G.J. and Hamayun, M.2009. Gibberellin production and phosphate solubilization by newly isolated strain of *Acinetobactercalcoaceticus* and its effect on plant growth. Biotechnol. Lett. 31:277-281.

Kapulnik, Y., Kiegel, J., Nur, I. and Henis, Y. 1981. Effect of temperature, nitrogen fertilization and plant age on nitrogen fixation by *Setariaitalica* inoculated with *Azospirillum brasilense* (strain Cd). Plant Physiol. 68:340-343.

Karnwal, A. 2009. Production of indol acetic acid by Fluorescent *Pseudomonas* in the presence of L-Tryptophan and Rice root exudates. J. Plant Pathol. 91: 61-63.

Kaur, R., Macleod, J., Foley, W. and Nayudu, M. 2006. Gluconic acid, an antifungal agent produced by Pseudomonas species in biological control of take all. Phytochemistry 67:595-604

Kaur, H., Kaur, J. and Gera, R. 2016. Plant Growth Promoting Rhizobacteria: A Boon to Agriculture. Int. J. Cell Sci. Biotech. 5: 17-22

Khalid, A., Akhtar, M.J., Mahmood, M.H. and Arshad, M. 2006. Effect of substrate-dependent microbial ethylene production on plant growth. Microbiology 75:231-236

Khan, A.G. 2005. Role of soil microbes in the rhizospheres of plant growing on trace metal contaminated soils in phytoremediation. J. Trace. Elem. Med. Biol. 18:355-364

Khan, M.S., Zaidi, A. and Aamil, M. 2002. Biocontrol of fungal pathogens by the use of plant growth promoting rhizobacteria and nitrogen fixing microorganisms. Indian. J. Bot Soc. 81:255–263

Khan, M.S., Zaidi, A. and Wani, P.A. 2007. Role of phosphate solubilizing microorganisms in sustainable agriculture- a review. Agron. Sustain. Dev. 27:29-43.

Khan, Z.R., Midega, C.A.O., Pittchar. J.O., Murage, A.W., Birkett, M.A, Bruce, T.J.A et al. 2014. Achieving food security for one million sub-Saharan African poor through push-pull innovation by 2020. Philosophical Transactions of the Royal Society B, 369(1639), 20120284.

Kloepper, J.W., Leong, J., Teintze, M. and Schroth, M.N 1980. Enhanced plant growth by siderophores produced by plant growthpromoting rhizobacteria. Nature, 286: 885-886.

Labuschagne, N., Pretorius, T. and Idris, A.H. 2010. Plant growth promoting rhizobacteria as biocontrol agents against soil-borne plant diseases. In: Maheshwari DK (ed) Plant growth and health promoting bacteria, Microbiology monographs. Springer, Berlin, pp 211–230

Lanteigne, C., Gadkar, V.J., Wallon T, Novinscak, A. and Filion, M. 2012. Production of DAPG and HCN by P*seudomonas* sp. LBUM3s00 contributes to the biological control of bacterial canker of tomato. Phytopathology 102:967-973.

Laville, J., Blumer, C., Von Schroetter, C., Gaia, V., De fago, G., Keel, C., Haas, D. 1998. Characterization of the hcnABC gene cluster encoding hydrogen cyanide synthase and anaerobic regulation by ANR in the strictly aerobic biocontrol agent *Pseudomonas fuorescens* CHA0. J. Bacteriol. 180: 3187-3196.

Li, K., Ramakrishna, W. 2011. Effect of multiple metal resistant bacteria from contaminated lake sediments on metal accumulation and plant growth. J. Hazard. Mater. 189:531-539

Long, S.R. 2001. Genes and signals in the Rhizobium-legume symbiosis. Plant Physiol. 125: 69-72.

Loper, J.E. and Henkels, M.D. 1999. Utilization of heterologous siderophores enhances levels of iron available to *Pseudomonas putida* in the rhizosphere. Appl. Environ. Microbiol. 65: 5357-5363.

Loper, J.E. 1988. Role of fluorescent siderophore production in biological control of *Pythium ultirnum* by a *Pseudomonas fluorescens* strain. Phytopathology.78:166-172.

Lorck, H. 1948. Production of Hydrocyanic Acid by Bacteria. Physiol. Plant.1: 142-146.

Lugtenberg, B. and Kamilova, F. 2009. Plant-growth-promoting bacteria. Annu. Rev. Microbiol. 63:541-556

Lugtenberg, B.J.J., Dekkers, L. and Bloemberg, G.V. 2001. Molecular determinants of rhizosphere colonization by Pseudomonas. Annu. Rev. Phytopathol. 39:461-490

Lugtenberg, B. and Kamilova, F. 2009. Plant-growth-promoting rhizobacteria. Annu. Rev. Microbiol.63: 541-556.

Ma, Y., Rajkumar, M. and Freitas, H. 2009. Improvement of plant growth and nickel uptake by nickel resistant-plant-growth promoting bacteria. J. Hazard. Mater. 166:1154-1161

Mabood, F., Zhou, X. and Smith, D.L. 2014. Microbial signaling and plant growth promotion. Can. J. Plant Sci. 94:1051-1063

Maggio, A., Barbieri, G., Raimondi, G. and de Pascale, S. 2010. Contrasting effects of GA3 treatments on tomato plants exposed to increasing salinity. J. Plant. Growth. Regul. 29:63-72

Mahdi, S.S., Hassan, G.I., Samoon, S.A., Rather, H.A., Dar, S.A. and Zehra, B. 2010. Biofertilizers in organic agriculture. J. Phytol.**2:** 42-54.

Maleki, M., Mostafaee, S., Mokhtarnejad, L. and Farzaneh, M. 2010. Characterization of Pseudomonas fluorescens strain CV6 isolated from cucumber rhizosphere in Varamin as a potential biocontrol agent. AJCS. 4(9):676-683

Mansour, F.A., Ildesuguy, H.S. and Hamedo, H.A. 1994. Studies on plant growth regulator sand enzyme production by some bacteria. J. Qatar Univ. Sci. 14:81-288.

Markowich, N.A. and Kononova, G.L. 2003. Lytic enzymes of Trichoderma and their role in plant defense from fungal diseases: a review. Appl. Biochem. Microbiol. 39:341-351

Marschner, H. 1995. Mineral Nutrition of Higher Plants. San Diego, CA: Academic Press

Merchan, F., de Lorenzo, L., González-Rizzo, S., Niebel, A., Megías, M., Frugier, F., Sousa, C. and Crespi, M. 2007. Analysis of regulatory pathways involved in the reacquisition of root growth after salt stress in Medicago truncatula. Plant. J. 51:1-17

Mia, M.A.B., Shamsuddin, Z.H. and Maziah, M. 2010. Use of Plant Growth Promoting Bacteria in Banana: A New Insight for Sustainable Banana Production. Int. J. Agric. Biol., 12(3): 459 467.

Miller, M.B. and Bassler, B.L. 2001. Quorum sensing in bacteria. Annu Rev Microbiol 55:165-199

Miller, M.J. and Malouin, F. 1994. Siderophore-mediated drug delivery: the design, synthesis, and study of siderophore-antibiotic and antifungal conjugates. In. Microbial iron chelates, ed. Bergeron R, Boca Raton, Fla: CRC Press. pp. 275-306.

Minuto, A., Spadaro, D., Garibaldi, A., Gullino, M.L. 2006. Control of soilborne pathogens of tomato using a commercial formulation of *Streptomy cesgriseoviridis* and solarization. Crop Protect. 25: 468-475.

Nakkeeran, S., Fernando, W.G.D., Siddiqui, Z.A. 2005. Plant growth promoting rhizobacteria formulations and its scope in commercialization for the management of pests and diseases. In: Siddiqui, Z.A. (Ed.), PGPR: Biocontrol and Biofertilization, Springer, Dordrecht, The Netherlands. ISBN 978-1-4020-4152-5, pp. 257-296.

Neilands, J.B. 1989. Siderophore systems of bacteria and fungi. In: Doyle, R.J. (Eds), Metal Ions and Bacteria. John Wiley and Sons, New York. 141-163.

Ngumbi, E. and Kloepper, J. 2016. Bacterial-mediated drought tolerance: Current and future prospect. Appl. Soil Ecol.105, 109-125

Niranjan, R., Shetty, H.S., Reddy, M.S. 2005. Plant growth-promoting rhizobacteria: potential green alternative for plant productivity. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, pp 197-216

Nisha, K.,Padma Devi, S.N., Vasandha, S., Sunitha kumara, K. 2014. Role of Phosphorous Solubilizing Microorganisms to Eradicate P Deficiency in Plants: A Review. Int. J. Sci. Res. 4:1-5.

Noordman, W.H., Reissbrodt, R., Bongers, R.S., Rademaker, I.L.W., Bockelmann, W. and Smit, G. (2006). Growth stimulation of *Brevibacterium* sp. by siderophores. J. Appl. Microbiol. 101:637–646

Normanly, J. 1997. Auxin metabolism. Physiology. Plantarum.100: 431-442.

Noumavo, P.A., Agbodjato, N.A., Baba-Moussa, F., Adjanohoun. A., Baba-Moussa, L. 2016. Plant growth promoting rhizobacteria: Beneficial effects for healthy and sustainable agriculture. Afr. J. Biotech.15 (27): 1452-1463.

O´Sullivan, D.J. and O´Gara, F. 1992. Traits of fluorescent Pseudomonas *spp*. involved in suppression of plant root pathogens. Microbiol. Rev. 56: 662-676

Palumbo, J.D., Yuen, G.Y., Jochum. CC., Tatum, K., Kobayashi, D.Y. 2005. Mutagenesis of beta 1, 3-glucanase genes in Lysobacter enzymogenes strain C3 results in reduced biological control activity toward Bipolaris leaf spot of tall fescue and Pythium damping-off of sugar beet. Phytopathology 95:701–707

Patten, C.L. and Glick, B.R. 2002. Role of *Pseudomonas putida* indole acetic acid in development of the host plant root system. Appl. Environ. Microbiol. 68:3795-3801.

Penrose, D.M. and Glick, B.R. 2001. Levels of 1-aminocyclopropane-1-carboxylic acid (ACC) in exudates and extracts of canola seeds treated with plant growth-promoting bacteria. Can. J. Microbiol. 47:368-372

Pérez-Montano, F., Alías-Villegas, C., Bellogín, R.A., del Cerro, P., Espuny, M.R., Jiménez-Guerrero. I., López-Baena, F.J., Ollero, F.J. and Cubo, T. 2014. Plant growth promotion in cereal and leguminous agricultural important plants: From microorganism capacities to crop production. Microbiol. Res. 169:325-336.

Perneel, M., D'hont, L., De, Maeyer, K.,Adiobo, A., Rabaey, K.and H€ofte M. 2008. Phenazines and biosurfactants interact in the biological control of soil-borne diseases caused by Pythium spp. Environ Microbiol 10:778-788

Perret, X., Staehelin, C. and Broughton, W.J. 2000. Molecular basis of symbiotic promiscuity. Microbiol. Mol. Biol. Rev. 64: 180-201.

Perrott, K.W., Sarathchandra, S.U., Dow, B.W. 1992. Seasonal and fertilizer effects on the organic cycle and microbial biomass in a hill country soil under pasture. Aust. J. Soil Res. 30 (3): 383-394. https://doi.org/10.1071/SR9920383

Persello-Cartieaux, F., Nussaume, L. and Robaglia, C. 2003. Tales from the underground: molecular plant-rhizobacteria interactions. Plant Cell Environ. 26: 189-199.

Petersen, S.O. and Klug, M.J. 1994. Effects of sieving, storage and incubation temperature on the phospholipid fatty acid profile of a soil microbial community. Appl. Environ. Microbiol. 60, 2421-2430

Pierik, R., Tholen, D., Poorter, H., Visser, E.J. and Voesenek, L.A. 2006. The Janus face of ethylene: growth inhibition and stimulation. Trends plant sci. 11**,** 176-183.

Pieterse, C.M.J., Zamioudis, C., Berendsen, R.L., Weller, D.M., VanWees, S.C. and Bakker, P.A. 2014. Induced systemic resistance by beneficial microbes. Annu Rev Phytopathol 52:347-375

Pilet, P.E. and Saugy, M. 1987. Effect of root growth of endogenous and applied IAA and ABA. A critical reexamination. Plant Physiol. 83:33-38.

Pliego, C., Kamilova, F. and Lugtenberg, B. 2011. Plant growth-promoting bacteria: fundamentals and exploitation In: Maheshwari DK (Ed.) Bacteria in Agrobiology Crop Ecosystems. Heidelberg. Springer. pp. 295-343.

Podile, A.R. and Kishore, G.K. 2006. Plant growth-promoting rhizobacteria. In: Gnanamanickam, S.S. (Ed.), Plant-Associated Bacteria. Springer, The Netherlands, ISBN 978-1-4020-4538-7, pp. 195-230.

Pospíšilová, J. 2003a. Interaction of cytokinins and abscisic acid during regulation of stomatal opening in bean leaves. Photosynthetica 41: 49-56

Pospíšilová, J. 2003b.Participation of phytohormones in the stomatal regulation of gas exchange during water stress. Biol. Plant. 46:491-506

Prapagdee, B., Kuekulvong, C. and Mongkolsuk, S. 2008. Antifungal potential of extracellular metabolites produced by *Streptomyces hygroscopicus* against phytopathogenic fungi. J. Biol. Sci. 4: 330-337.

Qurashi, A.W. and Sabri, A.N. 2012. Bacterial exopolysaccharide and biofilm formation stimulate chickpea growth and soil aggregateon under salt stress. Braz. J. Microbiol.43, 1183-1191.

Radi, A.F., Shaddad, M.A.K., El-Enany, A.E. and Omran, F.M. 2006. Interactive effects of plant hormones (GA3 or ABA) and salinity on growth and some metabolites of wheat seedlings. Develop Plant Soil Sci. Plant Nutr. 92:436–437

Ramachandran, K., Srinivasan, V., Hamza, S. and Anadaraj, M. 2007. Phosphate solubilizing bacteria isolated from the rhizosphere soil and its growth promotion on black pepper (*Piper nigrum* L.) cutting. Plant Soil Sci. 102:325-331.

Richardson, A.E. and Simpson, R.J. 2011. Soil microorganisms mediating phosphorus availability. Plant Physiology, 156, 989-996

Robin, A., Vansuyt, G., Hinsinger, P., Meyer, JM., Briat, J.F. and Lemanceau, P. 2008. Iron dynamics in the rhizosphere: consequences for plant health and nutrition. Adv. Agron. 99:183-225.

Rodriguez, H. and Fraga, R. 1999. Phosphate solubilizing bacteria and their role in plant growth promotion. Biotechnol. Adv. 17: 319-339

Sagervanshi, A., Kumari, P., Nagee, A. and Kumar, A. 2012. Isolation and Characterization of Phosphate Solublizing Bacteria from Anand Agriculture Soil. Int. J. Life Sci. Pharma Res. 23:256-266.

Saharan, B.S. and Nehra, V. 2011. Plant growth promoting rhizobacteria: a critical review. Life Sci Med Res 2011:1-30.

Sandhya, V., Ali, S.Z., Grover, M., Reddy, G. and Venkateswaralu, B. 2010. Effect of plant growth promoting Pseudomonas sp. On compatable solutes antioxidant status and plant growth of maize under drought stress. Plant Growth Regu

Saraf, M., Jha, C.K. and Patel, D. 2011. The Role of ACC Deaminase Producing PGPR in Sustainable Agriculture. In: Maheshwari DK, editor. Plant Growth and Health Promoting Bacteria Microbiology, Monographs vol. 18, series editor Steinbuchel A. Germany: Springer; 2011. pp. 365-386.

Schoenborn, L., Yates, P.S., Grinton, B.E., Hugenholtz, P. and Janssen, P.H. 2004. Liquid serial dilution is inferior to solid media for isolation of cultures representative of the phylum-level diversity of soil bacteria. Appl. Environ. Microbiol. 70:4363-4366.

Schultze, M. and Kondorosi, A.1998. Regulation of symbiotic root nodule development. Annu Rev Genet 32: 33-57

Sheng, X.F., Xia, J.J., Jiang, C.Y., He, L.Y. and Qian, M. 2008. Characterization of heavy metal-resistant endophytic bacteria from rape (*Brassica napus*) roots and their potential in promoting the growth and lead accumulation of rape. Environ Pollut 156:1164-1170

Shobha, G. and Kumudini, B.S. 2012. Antagonistic effect of the newly isolated PGPR *Bacillus* spp. on *Fusarium oxysporum*. Int. J. Appl. Sci. Eng. Res. 1:463-474.

Shuhegger, R., Ihring, A., Gantner, S., Bahnweg, G., Knaooe, C., Vogg, G., Hutzler, P., Schmid, M., Van Breusegem, F., Eberl, L., Hartmann, A. and Langebartels, C. 2006. Induction of systemic resistance in tomato plants by N-acyl-L-homoserine lactone producing rhizosphere bacteria. Plant Cell Environ 29:909-918

Sivasakthi, S., Usharani, G. and Saranraj, P. 2014. Biocontrol potentiality of plant growth promoting bacteria (PGPR)-Pseudomonas fluorescens and Bacillus subtilis: A review." Afr. J. Agri. Res.9, 1265-1277.

Spaink, H.P. 2000. Root nodulation and infection factors produced by rhizobial bacteria. Annu. Rev. Microbiol. 54**:**257-288.

Steinshamn, H., Thuen, E., Bleken, M.A., Brenoe, U.T., Ekerholt, G. and Yri, C. 2004. Utilization of nitrogen (N) and phosphorus (P) in an organic dairy farming system in Norway. Agriculture Ecosystems and Environmental. 104: 509-522

Sundara, B., Natarajan, V. and Hari, K. 2002. Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugarcane and sugar yield. Field Crop Res. 77: 43-49.

Sureshbabu, K., Amaresan, N. and Kumar, K. 2016. Amazing Multiple Function Properties of Plant Growth Promoting Rhizobacteria in the Rhizosphere Soil. Int. J. Curr. Microbiol. App. Sci.5 (2): 661 683. doi: http://dx.doi.org/10.20546/ijcmas.2016.502.074

Tian F, Ding Y, Zhu H, Yao L, Du B (2009). Genetic diversity of siderophore-producing bacteria of tobacco rhizosphere. Braz. J. Microbiol. 40 (Suppl 2): 276-284.

Tilak, K.V.B.R., Ranganayaki, N., Pal, K.K., De, R., Saxena, A.K., Sekhar Nautyal, C., Shilpi, M., Tripathi, A.K. and Johri BN (2005). Diversity of plant growth and soil health supporting bacteria. Curr. Sci. 89:136-150.

Tilman, D. 1998. The greening of the green revolution. Nature. 396: 211-212

Timmusk, S., Paalme, V., Pavlicek, T., Bergquist, J., Vangala, A., Danilas, T. and Nevo, E. 2011. Bacterial distribution in the rhizosphere of wild barley under contrasting microclimates. PLoS One 6(3):e17968.

Van der Helm, D. and Winkelmann, G. 1994. Hydroxamates and polycarbonates as iron transport agents (siderophores) in fungi. In:

Van Loon, L.C. 2007. Plant responses to plant growth-promoting rhizobacteria. Eur. J. Plant Pathol. 119:243-254.

Van Veen, J.A., Van Overbeek, L.S.and Van Elsas, J.D. 1997. Fate and Activity of Microorganisms Introduced into Soil. Microbiol. Mol.Boil. Rev. 61:121-135.

Vazquez, P., Holguin, G., Puente, M.E., Lopez-Cortes, A. and Bashan Y (2000). Phosphate-solubilizing microorganisms associated with the rhizosphere of mangroves in a semiarid coastal lagoon. Biol. Fertil. Soils 30:460-468.

Vessey, J.K. 2003. Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571-586.

Vettakkorumakankav, N.A. 1999. Crucial role for gibberellin in stress protecting of plants. Plant Cell Physiol. 40:542-548

Vikram, A. and Hamzehzarghani, H. 2008. Effect of phosphate solubilizing bacteria on nodulation and growth parameters of greengram (*Vignaadiate* L. Wilczek*)*. Res. J. Microbiol. 3:62-72.

Vivas, A., Biru, B., Ruiz-Lozano, J.M. and Azcon, R. 2006. Two bacterial strains isolated from Zn-polluted soil enhance plant growth and micorrhizal ef fi ciency under Zn toxicity. Chemosphere 52:1523-1533

Voisard, C., Keel, C., Haas, D. and Defago, G.1989. Cyanide production *by Pseudomonas fluorescens* helps suppress black root rot of tobacco under gnotobiotic conditions. EMBO Journal. 8: 351-358.

Wan, M., Li, G., Zhang, J., Jiang, D. and Huang, H.C. 2008. Effect of volatile substances of *Streptomyces platensis* F-1 on control of plant fungal diseases. Biol. Contr. 46: 552-559.

Weyens, N., Truyens, S., Dupae, J., Newman, L., van der Lelie, D., Carleer, R. and Vangronsveld, J. 2010. Potential of *Pseudomonas putida* W619-TCE to reduce TCE phytotoxicity and evapotranspiration in poplar cuttings. Environ. Pollut. 158:2915-2919.

Whipps, J.M. 2001. Microbial interactions and biocontrol in the rhizosphere. J. Exp. Bot. 52:487-511.

Yamaguchi, S. 2008. Gibberellin metabolism and its regulation. Annu. Rev. Plant. Physiol. 59:225-251

Yasari, E. and Patwardhan, A.M. 2007. Effects of *Aztobacter* and *Azospirillium* inoculations and chemical fertilizers on growth and productivity of Canola. Asian J. Plant Sci. 77-82.

Yaxley, J., Ross, J., Sherriff, L. and Reid, J.B. 2001. Gibberellin biosynthesis mutations and root development in pea. Plant Physiol.125, 627-633.

Yazdani, M., Bahmanyar, M.A., Pirdashti, H. and Esmaili, M.A. 2009. Effect of Phosphate solubilization microorganisms (PSM) and plant growth promoting rhizobacteria (PGPR) on yield and yield components of Corn (*Zea mays* L.). Proc. World Acad. Sci. Eng. Technol. 37:90-92.

Yu, X., Liu, X., Zhu, TH., Liu, G.H. and Mao, C. 2012. Co-inoculation with phosphate-solubilizing and nitrogen- fixing bacteria on solubilization of rock phosphate and their effect on growth promotion and nutrient uptake by walnut. Eur. J. Soil. Biol. 50:112-117

Zahir, Z.A., Arshad, M. and Frankenberger Jr, W.T. 2004. Plant growth promoting rhizobacteria: Applications and perspectives in agriculture. Adv. Agron. 81:97-168.

Zahir, Z.A., Shah, M.K., Naveed, M. and Akhtar, M.J. 2010. Substrate dependent auxin production by *Rhizobium phaseoli* improve the growth and yield of *Vigna radiate* L. under salt stress conditions. J. Microbiol. Biotechnol. 20:1288-1294

Zahran, H.H. 2001. Rhizobia from wild legumes: diversity, taxonomy, ecology, nitrogen fixation and biotechnology. J. Biotechnol. 91:143-153. doi:10.1016/S0168-1656(01)00342-X

Zaidi, A., Khan, M.S., Ahemad, M., Oves, M. and Wani, P.A. 2009. Recent Advances in Plant Growth Promotion by Phosphate-Solubilizing Microbes. In. Microbial Strategies for Crop Improvement, ed. Khan MS, Berlin Heidelberg: Springer-Verlag. pp. 23-50.

Zaidi, S., Usmani, S., Singh, B.R. and Musarrat, J. 2006. Significance of *Bacillus subtilis* strain SJ 101 as a bioinoculant for concurrent plant growth promotion and nickel accumulation in *Brassicajuncea* . Chemosphere 64:991-997

Zehnder, G.W., Murphy, J.F., Sikora, E.J. and Kloepper, J.W. 2001. Application of rhizobacteria for induced resistance. Eur. J. Plant. Pathol. 107:39-50

Zhuang, X., Chen, J., Shim, H. and Bai, Z. 2007. New advances in plant growth-promoting rhizobacteria for bioremediation. Environ. Int. 33 (3): 406-413. PMID: 17275086 DOI: 10.1016/j.envint.2006.12.005

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