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Review

Microbial intervention in agriculture: An overview

Amrita Sengupta* and Sunil Kumar Gunri

Department of Agronomy, Faculty of Agriculture, Bidhan Chandra Krishi Viswavidyalaya, Nadia – 741252, West Bengal, India.

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With increase in population, rapid urbanization and industrialization, land area under agricultural production is decreasing day by day. In order to feed the huge population, more production is required from lesser area, which triggers continuous applications of higher doses of inorganic fertilizers in an injudicious manner posing serious harm on soil health, further rendering large fraction of land unfit for cultivation every year due to nutrient imbalance. Combustion of fossil fuels during production of inorganics, leaching, loss of excess inorganic nitrate and phosphorus from cropped lands, excessive uplifting of ground water for irrigation purpose also lead to degradation of the quality of environment and natural resources through global warming, eutrophication, heavy metal contamination in ground water, etc. Under such circumstances, some improvised technologies are to be adopted to enhance productivity in a sustainable manner. A great deal of effort focusing on the soil biological system and the agro-ecosystem as a whole is needed to enable better understanding of the complex processes and interactions governing the stability of agricultural lands. The technological advances made in recent times in exploring biodiversity have revealed that microbial diversity has immense potential that can be explored through careful selection of microbes and their successful utilization in solving major agricultural and environmental issues.

Key words: Agriculture, biological nitrogen fixation (BNF), plant growth promoting rhizobacteria (PGPR), phosphate solubilizing microorganisms, vesicular arbascularmicorrhizae (VAM), arsenic detoxification.

INTRODUCTION

The soil rhizosphere is a huge reservoir of microbial diversity. Microbes perform numerous metabolic functions essential for their own maintenance and can benefit the biosphere directly or indirectly through nutrient recycling, environmental detoxification, soil health improvement, waste water treatment, etc. A large fraction of beneficial soil microorganisms are still undiscovered and their ecological functions are quite unknown. Therefore, vast assays of microbial activities are the basic steps towards development of new technologies for efficient utilization of microorganisms for attainment of sustainability in agriculture.

The greatest threats of the twenty-first century have become quite clear in the last few years. Climate change due to the vast increase in the production of greenhouse gases is real (Crowley, 2000). There is a genuine need for renewable energy supplies (Cook et al., 1991; Jackson, 1999). The diverse community of microorganisms constitutes “a metagenome of knowledge”. This metagemone also extends to the microbial communities

*Corresponding author. E-mail: amritasenbckv@gmail.com.

both inside and out of our body (Ahmad et al., 2011). Thus, microbial intervention in combination with developments in electronics, digital imaging and nanotechnology may play a major role in solving global challenges of the twenty first century including climate change.

MICROBIAL INTERVENTION: WHAT IS IT?

It is the action or process of intervening biological processes in soil or in plants/plant roots by the micro organisms present in the rhizosphere which is mostly beneficial for enhancement of nutrient availability as well as growth and yield of crops.

Microbial intervention may be helpful in attaining higher productivity with sustainability in agriculture in many ways, like: fixation of atmospheric nitrogen, increased availability of plant nutrients, decomposition and recycling of organic wastes and residues, bioaccumulation or microbial leaching of inorganics (Brierley 1985; Ehrlich 1990), suppression of soil-borne pathogens, bio-degradation of toxicants including pesticides, production of antibiotics and other bioactive compounds, production of simple organic molecules for plant uptake, complexation of heavy metals to limit plant uptake, solubilization of nutrient sources, production of polysaccharides to improve soil aggregation and many more.

This review article aims to cover the perspective of soil-beneficial bacteria and their role in plant growth promotion via direct and indirect mechanisms. Further elucidation of mechanisms involved will help to make these bacteria a valuable tool in agro-ecology in the near future.

Plant growth promoting rhizobacteria

In the era of sustainable crop production, the plant-microbe interactions in the rhizosphere plays a pivotal role in transformation, mobilization, solubilization, etc. of nutrients from a limited nutrient pool, and subsequently uptake of essential nutrients by plants to realize their full genetic potential. At present, the use of biological approaches is becoming more popular as an additive to chemical fertilizers for improving crop yield in an integrated plant nutrient management system. In this regard, the use of plant growth promoting rhizobacteria (PGPR) has found a potential role in developing sustainable systems in crop production (Sturz et al., 2000; Shoebitz et al., 2009), though, the mechanisms of PGPR-mediated enhancement of plant growth and yield of many crops are not yet fully understood (Dey et al., 2004).

PGPRs have different relationships with different host plants. The two major classes of relationships are rhizospheric and endophytic. Rhizospheric relationships consist of the PGPRs that colonize the surface of the root, or superficial intercellular spaces of the host plant, often forming root nodules. The dominant species found in the rhizosphere is a microbe from the genus *Azospirillum* (Bloemberg and Lugtenberg, 2001). Endophytic relationships involve the PGPRs residing and growing within the host plant in the apoplastic space (Vessy, 2003).

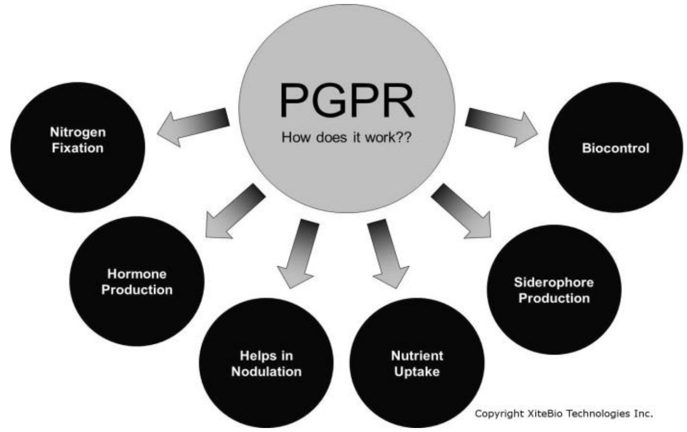

Figure 1. Beneficial functions of PGPR. Source: http://blog.xitebio.ca/6-ways-bacteria-promote-healthier-plants.

PGPR also help in solubilization of mineral phosphates and other nutrients, enhance resistance to stress, stabilize soil aggregates, and improve soil structure and organic matter content. PGPR retain more soil organic N, and other nutrients in the plant-soil system, thus they help in reducing the need for N and P fertilizer and enhance release of the nutrients. Beneficial effects of PGPR have been depicted in Figure 1.

Beneficial functions of PGPR

Direct plant growth promotion on the other hand, involves symbiotic and non-symbiotic PGPR functioning through production of plant hormones such as auxins, cytokinins, gibberellins, ethylene and abscisic acid. Production of indole-3-ethanol or indole-3-acetic acid (IAA), the compounds belonging to auxins, have been reported for several bacterial genera. Some PGPR function as a sink for 1-aminocyclopropane-1-carboxylate (ACC), the immediate precursor of ethylene in higher plants, by hydrolyzing it into α-ketobutyrate and ammonia, and in this way promote root growth by lowering indigenous ethylene levels in the micro-rhizo environment (Hayat et al., 2010).

Nutrient supply function

Nitrogen fixing bacteria

Nitrogen is one of the most important essential nutrient elements for plant growth and development but

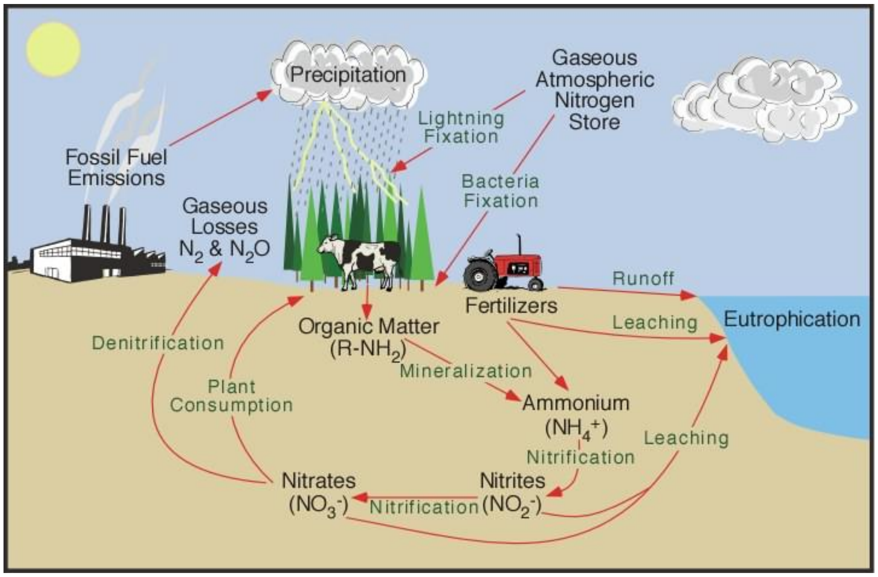

Figure 2. Nitrogen Cycle in terrestrial ecosystems. Source: http://www.physicalgeography.net.

unfortunately is unavailable in its most prevalent form as atmospheric nitrogen. Plants instead depend upon combined or fixed forms of nitrogen, such as ammonia and nitrate. Much of this nitrogen is provided to cropping systems in the form of industrially produced nitrogen fertilizers. Use of these fertilizers has led to worldwide, ecological problems, such as the formation of coastal dead zones.

Biological nitrogen fixation, on the other hand, offers a natural means of providing nitrogen for plants (Wagner, 2012) (Figure 2).

Benefits of using biological nitrogen fixation (BNF)

The process of biological nitrogen fixation (BNF) accounts for 65% of the nitrogen currently utilized in agriculture, and will continue to be important in future sustainable crop production systems (Matiru and Dakora, 2004). Important biochemical reactions of BNF occur mainly through symbiotic association of N_2-fixing microorganisms with legumes that converts atmospheric elemental nitrogen (N_2) into ammonia (NH_3) (Shiferaw et al., 2004). By inoculating legume seeds with appropriate rhizobia, farmers can ensure that they take advantage of the benefits of BNF listed below.

1) Economics: BNF reduces costs of production. Field trials have shown that the N captured by crops due to the use of rhizobia inoculants costing $3.00/ha is equal to fertilizer N costing $87.00.
2) Environment: The use of inoculants as alternatives to N fertilizer avoids problems of contamination of water resources from leaching and run off of excess fertilizer. Utilizing BNF is part of responsible natural resource management.
3) Efficiency: Legume inoculants do not require high levels of energy for their production or distribution. Application on the seed is simple as compared to spreading fertilizer on the field. Long-term leguminous tree crops are self-sustaining through BNF.
4) Better yields: Inoculants increase legume crop yields in many areas. BNF often improves the quality of dietary protein of legume seed even when yield increases are not detected.
5) Increased soil fertility: Through practices such as green manuring, crop rotations and alley cropping, N-fixing legumes can increase soil fertility, permeability, and organic matter to benefit non-legume crops.
6) Sustainability: Using BNF is part of the wise management of agricultural systems. The economic, environmental and agronomic advantages of BNF make it a cornerstone of sustainable agricultural systems. Legumes comprise one of the most important plant families in agriculture. Nitrogen-fixing members of this family include important food grains like soybeans, peas, beans and peanuts; forage crops like alfalfa and clover; and useful trees like leucaena and acacias (Silva and Uchida, 2000).

Types of micro-organisms involved in BNF at a glance

Number of symbiotic as well as non-symbiotic (free living) micro-organisms, that are present in soil rhizosphere, can help in BNF in a number of crop and/or non-crop plants (Figure 3).

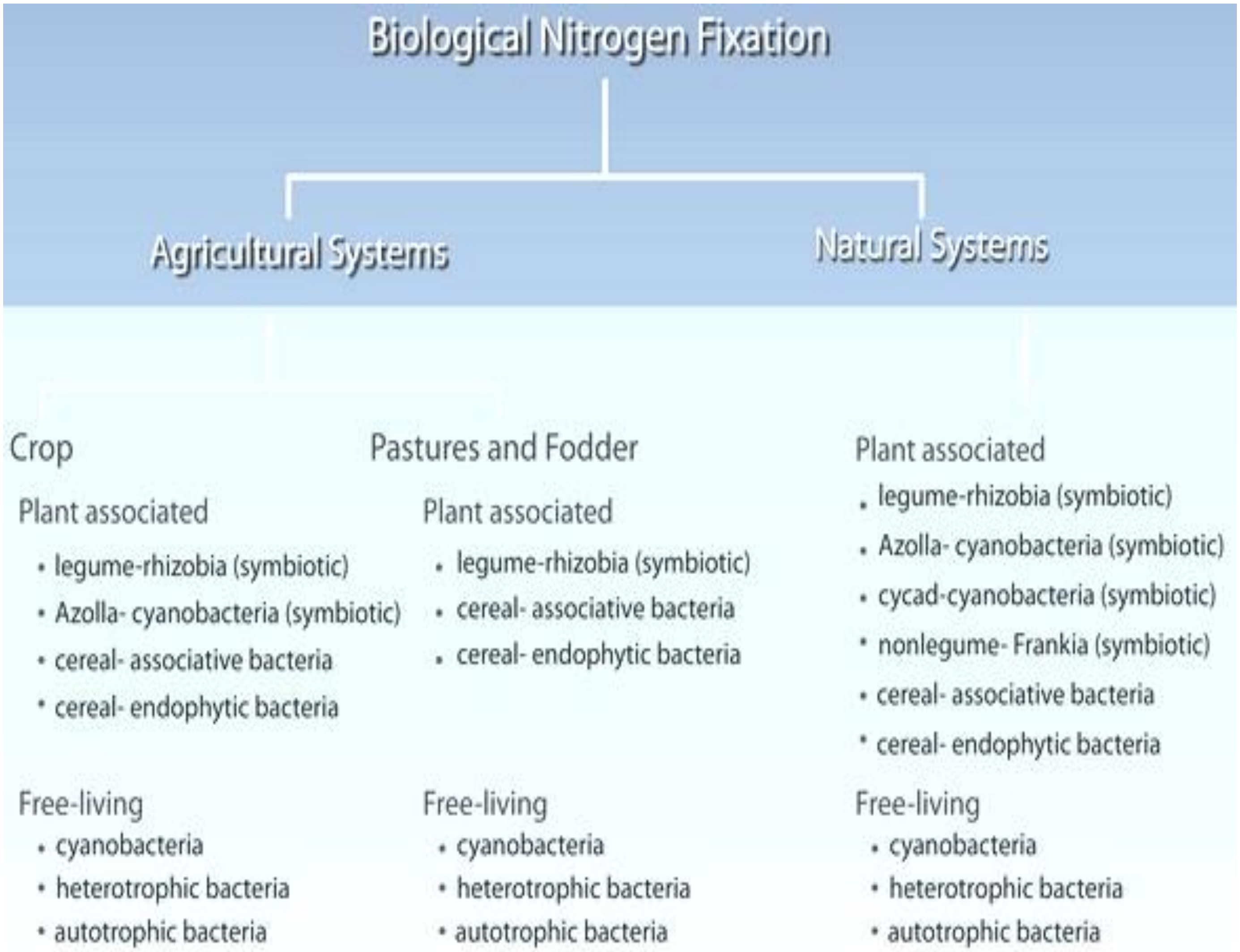

Figure 3. Types of microorganisms involved in BNF at a glance. Source: http://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419.

The nitrogen fixed by symbiotic *Rhizobia* in legumes can also benefit associated non-legumes via direct transfer of biologically fixed N to cereals growing in intercrops (Snapp et al., 1998) or to subsequent crops rotated with symbiotic legumes (Shah et al., 2003; Hayat, 2005; Hayat et al., 2008a, b). The plant nodule number and nodule weight increased with the age of the groundnut crop and highest was recorded at 60 days after sowing, when biofertilizer consortium was used with 10 t/ha of FYM (28.9 and 36.4 mg respectively) (Gunri and Nath, 2012). It was also found that biofertilizer application to red and lateritic soil of West Bengal, India, had a positive response to increase in pod and haulm yield of groundnut (Gunri et al., 2014). In many low input grassland systems, the grasses depend on the N_2 fixed by the legume counterparts for their N nutrition and protein synthesis, which is much needed for forage quality in livestock production (Paynel et al., 2001; Hayat and Ali, 2010). In addition to N_2-fixation in legumes, *Rhizobia* such as species of *Rhizobium* and *Bradyrhizobium* produce molecules (auxins, cytokinins, abscicic acids, lumichrome, rhiboflavin, lipochitooligosaccharides and vitamins) that promote plant growth (Hardarson, 1993; Herridge et al., 1993; Keating et al., 1998; Hayat and Ali, 2004; Hayat et al., 2008a, b). Their colonization and infection of roots would also be expected to increase plant development and grain yield (Kloepper and Beauchamp, 1992; Dakora, 2003; Matiru and Dakora, 2004). Other PGPR traits of *Rhizobia* and *Bradyrhizobia* include phytohormone production (Chabot et al., 1996a, b; Arshad and Frankenberger, 1998), siderophore release (Plessner et al., 1993; Jadhav et al., 1994), solubilization of inorganic phosphorus (Abd-Alla, 1994a; Chabot et al., 1996a) and antagonism against plant pathogenic microorganisms (Ehteshamul-Haque and Ghaffar, 1993). Besides rice, *Rhizobia* have also been isolated as natural endophyets from roots of other non-legumes species such as cotton, sweet corn (Mclnroy and Kloepper, 1995), maize (Martinez-Romero et al., 2000), wheat (Biederbeck et al., 2000) and canola (Lupwayi et al., 2000) either grown in rotation with legumes or in a mixed cropping system involving symbiotic legumes.

A range of non-symbiotic plant growth promoting rhizobacteria (PGPR) participate in interaction with C_3 and C_4 plants (e.g., rice, wheat, maize, sugarcane and cotton), and significantly increase their vegetative growth and grain yield (Kennedy et al., 2004). *Azotobacter* species (*Azotobacter vinelandii* and *Azotobacter chroococcum*) are free-living heterotrophic diazotrophs that depend on an adequate supply of reduced C compounds such as sugars for their energy source (Kennedy and Tchan, 1992). Their activity in rice culture can be increased by straw application (Kanungo et al., 1997), presumably as a result of microbial breakdown of cellulose into cellobiose and glucose. Yield of rice (Yanni and El- Fattah, 1999), cotton (Iruthayaraj, 1981; Patil and Patil, 1984; Anjum et al., 2007), and wheat (Soliman et al., 1995; Hegazi et al., 1998; Barassi et al., 2000) increased with the application of *Azotobacter*.

In contrast to *Azotobacter*, *Clostridia* are obligatory anaerobic heterotrophs only capable of fixing N_2 in the complete absence of oxygen (Kennedy and Tchan, 1992; Kennedy et al., 2004). *Clostridia* can usually be isolated from rice soils (Elbadry et al., 1999), and their activity also increased after returning straw to fields, raising the C to N ratio in the soil.

Azospirillum species are aerobic heterotrophs that fix N_2 under microaerobic conditions (Roper and Ladha 1995) and grow extensively in the rhizosphere of gramineous plants (Kennedy and Tchan, 1992; Kennedy et al., 2004). Beneficial effects of inoculation with *Azospirillum* on wheat yields in both greenhouse and field conditions have been reported (Hegazi et al., 1998; El Mohandes, 1999; Ganguly et al., 1999). Inoculation with *Azospirillum brasilense* significantly increases cotton plant height and dry matter under greenhouse conditions (Bashan, 1998). Soil applications with *Azospirillum* can significantly increase cane yield in both plant and ratoon crops in the field (Shankariah and Hunsigi, 2001). The PGPR effects also increase N and P uptake in field trials (Galal et al., 2000; Panwar and Singh, 2000), presumably by stimulating greater plant root growth. Substantial increases in N uptake by wheat plants and grain were observed in greenhouse trials with inoculation of *A. brasilense* (Islam et al., 2002). 15N tracer techniques showed that *A. brasilense* and *Azospirillum lipoferum* contributed 7-12 of wheat plant N by BNF (Malik et al., 2002).

The genus *Burkholderia* comprises 67 validly published species, with several of these including *Burkholderia vietnamiensis, Burkholderia kururiensis, Burkholderia tuberum* and *Burkholderia phynatum*being capable of fixing N_2 (Estrada-delos Station et al., 2001; Vandamme et al., 2002). When *B. vietnamiensis* was used to inoculate rice in a field trial, it increased grain yields significantly up t 8 t ha^{-1} (Tran Vân et al., 2000). There is also evidence that these organisms can produce substances antagonistic to nematodes (Meyer et al., 2000).

Herbaspirillum is an endophyte which colonises sugarcane, rice, maize, sorghum and other cereals (James et al., 2000). It can fix 31-45% of total plant N in rice (30-day-old rice seedling) and N from the atmosphere (Baldani et al., 2000). The estimated N fixation by *Herbaspirillum* was 33–58 mg $tube^{-1}$ under aseptic conditions (Reis et al., 2000). *Herbaspirillum seropedicae* also acts as anendophytic diazotroph of wheat plants (Kennedy and Islam, 2001), colonizing wheat roots internally between the cells.

Several species of family *Enterobacteriaceae* include diazotrophs, particularly those isolated from the rhizosphere of rice. These enteric genera containing some examples of diazotrophs with PGP activity include *Klebsiella, Enterobacter, Citrobacter, Pseudomonas* and probably several others yet unidentified (Kennedy et al., 2004).

Few research work tables validating the beneficial effects of nitrogen fixers in fixation of atmospheric nitrogen in soil

It is clear from Tables 1 and 2 nitrogen fixers are capable of fixation of atmospheric nitrogen symbiotically worldwide under varied edapho-climatic conditions in different host crops from the family leguminosae. Not only that, various non-symbiotic BNF are also there which have reported increase in yield (up to 50%) in cereals (rice) too.

Phosphorus-solubilizing bacteria

When compared with the other major nutrients, phosphorus is by far the least mobile and available to plants in most soil conditions. Although phosphorus is abundant in soils in both organic and inorganic forms, it is frequently a major or even the prime limiting factor for plant growth. The bioavailability of soil inorganic phosphorus in the rhizosphere varies considerably with plant species, nutritional status of soil and ambient soil conditions. When phosphatic fertilizers are applied to the soil, they often become insoluble (more than 70%) and are converted into complexes such as calcium phosphate, aluminum phosphate and iron phosphate in the soil (Mittal et al., 2008). Crop plants can therefore utilize only a fraction of applied phosphorus, which

Table 1. A summary of biological nitrogen fixation measurements by different legumes.

Crop	Location	Crop N (Kg N ha^{-1})		N_2 fixation (%)
		Total N	N_2 Fixed	
Soybean	Brazil (Boddey et al., 1990)	112-206	85-154	70-80
	Hawaii (George et al., 1988)	120-295	117-237	80-97
Groundnut	Australia (Peoples and Craswell 1992)	171-248	37-131	22-53
	India (Giller et al., 1987)	126-165	109-152	86-92
Common bean	Brazil (Duque et al., 1995)	18-71	3-32	16-71
Cowpea	Indonesia (Sisworo et al., 1990)	25-69	9-51	12-33

Table 2. Increase in rice grain yield and estimated amounts of fixed N_2 by different N_2 fixing systems (Choudhury et al., 2004).

N_2- fixator	Increase in rice yield		Estimated amount of N_2
	Amount	(%)	
Azolla-Anabaena symbiosis	1.5 t ha^{-1}	50	48.2 kg ha^{-1}
Cyanobacteria	1.4 t ha^{-1}	29	24.2 kg ha^{-1}
Azotobacter sp	0.4-0.9 t ha^{-1}	7- 20	11-15 kg ha^{-1}
Azospirillum lipoferum	6.7 g $plant^{-1}$	81	58.9% Ndfa
Herbaspirillum sp	3.7 - 7.5 g $plant^{-1}$	45 - 90	38.1 – 58.2% Ndfa
Burkholderia vietnamiensis	0.6 - 7.9 g pot^{-1}	13 - 22	Data not available
Rhizobium leguminosarum	0.6 - 7.9 g pot^{-1}	2 - 22	23 – 31 mg

Ndfa: Nitrogen derived from the atmosphere.

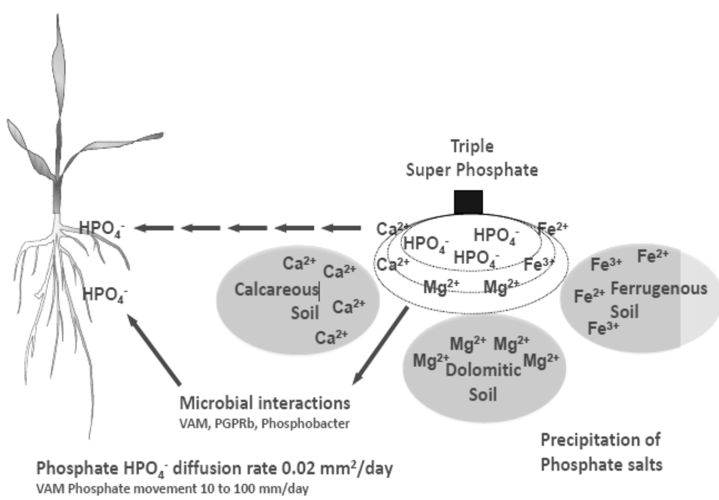

Figure 4. Microbes and phosphate conventional chemistry. Source: http://otc.nfmf.no/public/news/12380_2.pdf.

ultimately results in poor crop performance. To rectify this and to maintain soil fertility status, frequent application of chemical fertilizers is needed, though it is found to be a costly affair and also environmentally undesirable (Reddy et al., 2002).

To circumvent such phosphorus deficiency, phosphate-solubilizing microorganisms (PSM) could play an important role in supplying phosphate to plants in a more environment-friendly and sustainable manner (Figure 4). It has been suggested that accumulated phosphates in agricultural soils is sufficient to sustain maximum crop yields worldwide for about 100 years (Walpola and Yoon, 2012). Therefore, using potential phosphate solubilizers can definitely be a solution to render this huge phosphate bank available to the plant community.

Bacterial strains belonging to genera the *Pseudomonas,*

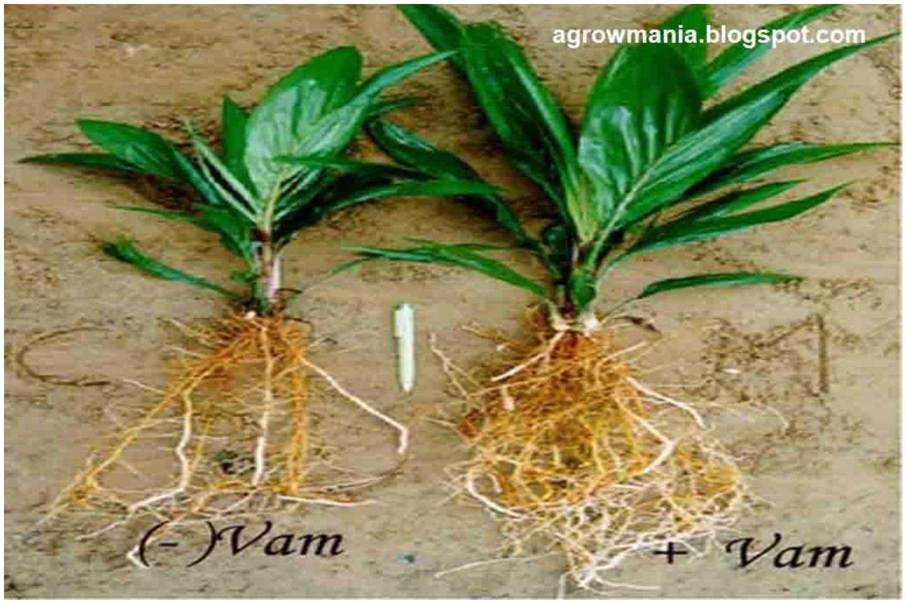

Figure 5. Inoculation with VAM. Source: http://agrowmania.blogspot.in/2009/06/biotech-solutions-to-organic_2227.html.

Bacillus, Rhizobium, Burkholderia, Achromobacter, Agrobacterium, Microccocus, Aerobacter, Flavobacterium and *Erwinia* have the ability to solubilize insoluble inorganic phosphate (mineral phosphate) compounds such as tricalcium phosphate, dicalcium phosphate, hydroxyl apatite and rock phosphate (Goldstein, 1986; Rodríguez and Fraga, 1999; Rodríguez et al., 2006). Strains from genera *Pseudomonas, Bacillus* and *Rhizobium* are among the most powerful phosphate solubilizers, while tricalcium phosphate and hydroxyl apatite seem to be more degradable substrates than rock phosphate (Arora and Gaur, 1979; Illmer and Schinner, 1992; Halder and Chakrabarty, 1993; Rodríguez and Fraga, 1999; Banerjee et al., 2006).

Integrated use of *Rhizobium,* PGPR containing ACC-deaminase in the presence of P-enriched compost would be a suitable approach for improving growth, yield and nodulation in lentil (Muhammad et al., 2012). Use of vesicular arbascularmicorrhizae (VAM) is also getting importance in this context. These are special types of soil micorrhizae that in association with plant roots, increase the root surface area and thereby improve soil-root contact, thus enhancing nutrient uptake by plants.

By applying VAM, the external mycelium extends several centimeters from the root surface and it then passes the depletion zone surrounding the root and exploits soil microhabitats beyond the nutrient depleted area where the small rootlets or root hairs cannot thrive. The phosphate is translocated into the mycelium in the root and is released for use by plants (Vishnu Sankar, 2009) (Figure 5).

Potassium (K) is the third major essential nutrient for plant growth. It plays an essential role for enzyme activation, protein synthesis and photosynthesis. There are dynamic equilibrium and kinetic reactions between the different forms of soil K that affect the level of soil solution K at any particular time, and thus, the amount of readily available K for plants. Some microorganisms in the soil are able to solubilize 'unavailable' forms of K-bearing minerals, such as micas, illite and orthoclase, by excreting organic acids which either directly dissolves rock K or chelating silicon ions to bring the K into solution (Bennett et al., 1998; Barker et al., 1998). A wide range of rhizosphere bacteria namely *Pseudomonas, Burkholderia, Acidothiobacillus ferrooxidans, Bacillus mucilaginosus, Bacillus edaphicus, B. circulans* and *Paenibacillus* sp. has been reported to release potassium in accessible form from potassium-bearing minerals in soils (Sheng, 2005; Lion et al., 2002; Li et al., 2006; Liu et al., 2012). These microorganisms are commonly known as potassium solubilizing bacteria (KSB) or potassium dissolving bacteria or silicate dissolving bacteria. Some research has been made on the use of potassium dissolving bacteria, known as "biological potassium biofertilizer (BPF)", particularly in China and South Korea to investigate the bio-activation of soil K-reserves so as to alleviate the shortage of K-fertilizer. It was shown that KSB increased K availability in soils and increased mineral uptake by plant (Sheng et al., 2002, 2003). Therefore, application of KSB holds a promising approach for increasing K availability in soils.

Inoculation with potassium solubilizing bacteria have been reported to exert beneficial effects on growth of cotton and rape (Sheng, 2005), pepper and cucumber (Han et al., 2006), sorghum (Badr et al., 2006), wheat (Sheng et al., 2006) and Sudan grass (Basak and and wheat plants with *Bacillus mucilaginosus*, *Azotobacter chroococcum* and *Rhizobium* resulted in significant higher mobilization of potassium from waste mica, which in turn acted as a source of potassium for plant growth (Singh et al., 2010).

Chemical and spectroscopic studies have shown that in agricultural soils, most of the soil sulphur (>95%) is present as sulphate esters or as carbon-bonded sulphur (sulphonates or amino acid sulphur), rather than inorganic sulphate. Plant sulphur nutrition depends primarily on the uptake of inorganic sulphate. However, recent research has demonstrated that the sulphate ester and sulphonate-pools of soil sulphur are also plant-bioavailable, probably due to interconversion of carbon-bonded sulphur and sulphate ester sulphur to inorganic sulphate by soil microbes. In addition to this mineralization of bound forms of sulphur, soil microbes are also responsible for the rapid immobilization of sulphate, first to sulphate esters and subsequently to carbon-bound sulphur. The rate of sulphur cycling depends on the microbial community present, and on its metabolic activity, though it is not yet known if specific microbial species or genera control this process. The genes involved in the mobilization of sulphonate- and sulphateester sulphur by one common rhizosphere bacterium, *Pseudomonas putida*, have been investigated. Mutants of this species that are unable to transform sulphate esters show reduced survival in the soil, indicating that sulphate esters are important for bacterial S nutrition in this environment. *P. putida* S-313 mutants that cannot metabolize sulphonate-sulphur do not promote the growth of tomato plants as the wild-type strain does, suggesting that the ability to mobilize bound sulphur for plant nutrition is an important role of this species (Kertesz and Mirleau, 2004).

Microbial intervention in soil-health improvement

Microorganisms, like different types of fungi, bacteria or actinomycetes present in soil help in degradation of soil organic matter and it's ingredients like polysaccharides-cellulose, hemicelluloses lignin, pectin etc and finally lead to formation of amorphous colloidal materials which is known as humus.

Being highly colloidal and amorphous in nature, humus exhibit high CEC and WHC, also reduces bulk density and soil plasticity resulting in fluffy crumby soil structure formation that is very much helpful for growing of crop plants.

Microbial intervention in suppression of soil borne pathogens: Building microbial defense

Building and maintaining the diversity and activity of beneficial soil microbes produces a defensive network around the plant roots which out compete disease organisms and provide protection for the plant. Some soil microorganisms caninhibit phyto-pathogens by the production of hydrogencyanide (HCN) and/or fungal cell wall degrading enzymes, for example, chitinase and β-1,3-glucanase.

In addition, beneficial microbes can help suppress many root feeding pests during their juvenile growth stages by utilizing them as food resources. Further, in order to improve microbial defense in soil, few steps can be followed:

1. Soil and plant tonic containing a broad diversity of beneficial and predatory microbes, which is an effective way to build-up microbial numbers and diversity are used.
2. Biofoods and stimulants can also be added, which provides food and stimulation for beneficial soil microbes to build and strengthen the population once they are introduced.
3. Maintaining good levels of organic carbon will also provide a favourable habitat for beneficial microbes and encourage their proliferation and survival.

Use of antibiotics

Many soil microorganisms develop antibiotics which help to destroy harmful pathogenic micro organisms and thereby support plant growth and development. For example, *Penicillium* sp., *Streptomyces* sp. present in soil produce penicillin and streptomycin, respectively, which inhibit the growth of many pathogenic micro organisms in soil by inhibition of cell wall, nucleic acid or protein synthesis, changes in metabolism, etc.

Microbial intervention in detoxification function

This function can further be divided into:

a) Complexation of heavy metals to limit plant uptake
b) Degradation of toxicants in pesticides.

Heavy metal detoxification

Heavy metal contamination due to natural and anthropogenic sources is a global environmental concern. Release of heavy metal without proper treatment poses a significant threat to public health because of its persistence, biomagnifications and accumulation in food chain. Non-bio degradability and sludge production are the two major constraints of metal treatment. Microbial metal bioremediation is an efficient strategy due to its low cost, high efficiency and eco-friendly nature. Recent advances have been made in understanding metal- microbe interaction and their application for metal accumulation/detoxification

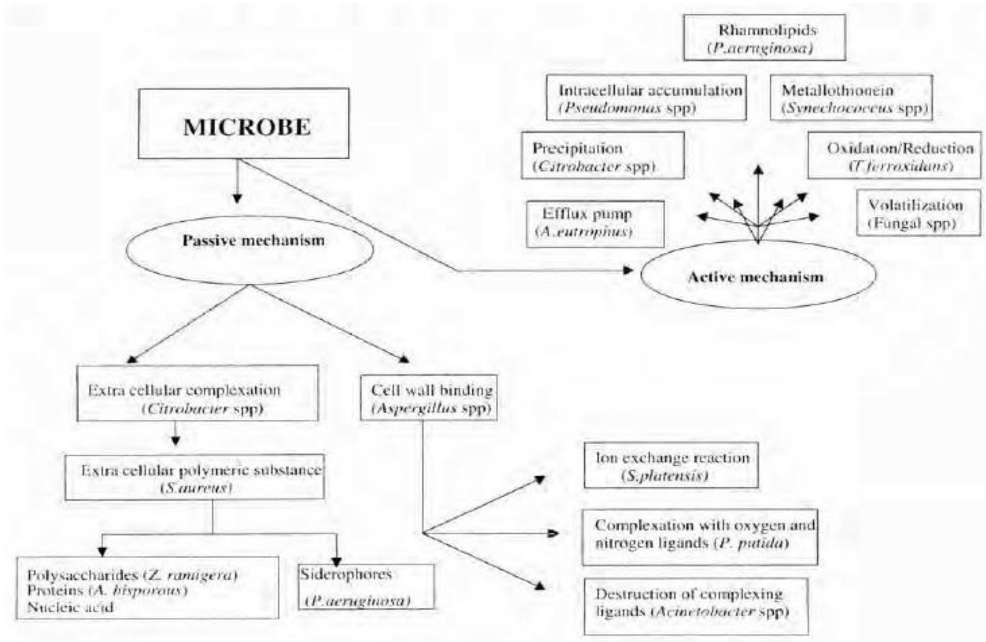

Figure 6. Mechanism of Microbial sorption.

(Rajendran et al., 2003).

There are a few metal elements (Ag, Cd, Sn, Au, Hg, Ti, Pb and Al) as well as metalloids (Ge, As, Sb and Se) that are considered as heavy metals and are found toxic in nature. The goal of microbial remediation of heavy metal contaminated soils and sediments are to immobilize the metal *in situ* to reduce metal bio-availability and mobility or to remove the metal from the soil. The mechanisms by which metal ions bind to the cell surface include electrostatic interactions, Van der Waals forces, covalent bonding, redox interactions and extracellular precipitation, or combination of these processes (Blanco, 2003).

Several active groups of cell constituents include acedamido group of chitin, structural polysaccharide of fungi (amino and peptidoglycosides), sulfhydral and carboxyl groups in protein, phospho-diester (teichoic acid), phosphate, hydroxyl in polysaccharides, participate in biosorption (Vasudevan et al., 2001). Microbial mediated heavy metal sorption mechanisms are described in the Figure 6.

Field applications of microbes in heavy metal toxicity bioremediation

The most important biotechnological application of metal-microbe interaction is in bioleaching, bioremediation, of polluted sites and mineralization of polluting organic matter.

Various microbially reducible metals, especially ferric iron in complexed form to keep it soluble at circum neutral pH, can be used as terminal electrol acceptors in *in situ* anaerobic bioremediation of sites polluted with toxic organics (Lovely, 1963). Fungi can convert oxidized selenium to volatile methylated selenides, to escape into the atmosphere (Frankenberger and Karlson, 1992), and bacteria can perform the methylation action on toxic arsenic metals resulting in their removal by volatilization. The increased rate of As (III) oxidation by native strains of *Bacillus* and *Geobacillus* might be exploited for the remediation of As in contaminated environments (Majumder et al., 2013). Twenty six arsenic (As) resistant bacterial strains were isolated from As contaminated paddy soil of West Bengal, India. Among them, 10 isolates exhibited higher arsenic resistance capacity and could be used as a potential bioremediator in future to combat with arsenic toxicity. Most probably these isolates were from *Bacillus* sp. (Majumder et al., 2013).

Microbes in degradation of toxicants in pesticides

Soil microbes can also help in degradation and detoxification of harmful active ingredients of pesticides applied in various crops as well as activation of putatively pesticide organo-molecules. Heterotrophic microbes generally tend to derive energy from the carbon molecules of these compounds and thus trigger their activation or deactivations in general.

CONCLUSIONS

Keeping in mind all these beneficial roles of microorganisms present in soil rhizosphere, it can be concluded that in the integrated nutrient management (INM) system, integration of microbial inoculants with less fertilizer should be considered in many situations as it promises high crop productivity and agricultural sustainability. The commercial use of PGPR also must await the development of coating technology to improve methods of storing and applying bacteria without loss of viability. Novel, genetically-modified soil and region specific micobial intervention and technologies for their ultimate transfer to the fields have to be developed, pilot-tested and transferred to farmers in a relatively short time. And last but not the least, search for new strains of beneficial micro-organisms for bio-fertilizer and development of microbial diversity map for any region just like nutrient mapping may be helpful too. Advance simulation models related to nature of microbes and their behavioural patterns under changing edapho-climatic conditions may also be developed with suitable technical calibrations and testing for better development and maintenance of agricultural sustainability as well as microbial diversity in the near future.

Conflict of interests

The authors did not declare any conflict of interest.

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