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REVIEW ARTICLE

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## Soil Microorganisms for Sustainable Agriculture: New Perspectives and Opportunities

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### ABSTRACT

The future of sustainable agriculture will progressively more rely on amalgamation of biotechnology with conventional agricultural practices. Though genetic engineering promises improved yields and disease resistance, it is important to distinguish that plants exist in intimate associations with microorganisms, some of which cause plant disease while others protect against disease. Identifying, understanding and utilizing microorganisms or microbial products to control plant disease and enhance crop production are integral parts of sustainable agriculture. Biological control has potential to control crop diseases while causing minimal detrimental environmental impact. Global agriculture has to double food production by 2050 in order to feed the world's growing population and reduce its reliance on inorganic fertilizers and pesticides. The microorganisms have been used over past 50 years to advance medical technology, food processing, safety and quality, genetic engineering, environmental protection, agricultural biotechnology and in more effective treatment of agricultural and municipal wastes collectively the most remarkable record. The competent and potential soil microbial biota is only suitable for sustainable agriculture practices and may not be the other options. Here in this review, competent soil microorganisms including N<sub>2</sub> fixing bacteria, PGPR, AMF, endophytic microorganisms, cyanobacteria, and bioremediation and biological control organisms are highlighted. **Keywords:** Arbuscular mycorrhizal fungi, Bioremediation, Cyanobacteria, Mycorrhizae, PGPR, Probiotics, Soil microbes.

### INTRODUCTION

Microbes such as fungi, bacteria and viruses play a vital role in sustainability of agriculture. Habitually, farmers think of microbes as pests that are destructive to their crops or animals, but many microbes are beneficial. Soil microbes especially bacteria and fungi are essential for decomposing organic matter and recycling old plant material.

Some soil bacteria and fungi form relationships with plant roots that provide important nutrients like nitrogen or phosphorus. Fungi can colonize upper parts of plants and provide many benefits, including drought tolerance, heat tolerance, resistance to insects and resistance to plant diseases. Some viruses that benefit to hosts and most probably do not harm their hosts. Microbes in terrestrial environments are important catalysts of global carbon and nitrogen cycles, including the production and consumption of greenhouse gases in soil. Some microbes produce the greenhouse gases carbon dioxide (CO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O) while decomposing organic matter in soil.

Others consume methane (CH<sub>4</sub>) from the atmosphere, thus helping to mitigate climate change. The importance of each of these processes is influenced by human activities and impacts the warming potential of Earth's atmosphere. Using contemporary genomic techniques, scientists analyzed DNA extracted directly from soil to assess which microbes were present and their metabolic potential. Communities of microbes were compared from three very different land use types *i.e.* row-crop agriculture (corn, soybean and wheat rotations), old fields that had been abandoned from agriculture for decades and deciduous forests. Because these treatments had been in place for 20-50 years, scientists were able to measure the long-term impacts of land management. It is suggested that managing lands to conserve or restore the diversity of methane-consuming bacteria could help mitigate climate change. Likewise, land management also seems to greatly affect the diversity of microbes involved in nitrous oxide production; fertilized soils produce more nitrous oxide and have a very different genetic makeup. The agriculture distinctly influences the diversity of bacteria responsible for the production and consumption of two of the three major naturally-occurring greenhouse gases. The uniqueness of microorganisms and their unpredictable nature and biosynthetic capabilities, given a specific set of environmental and cultural conditions, has made them likely candidates for solving particularly difficult problems in the life sciences and other fields as well. The various ways in which microorganisms have been used over the past 50 years to advance medical technology, human and animal health, food processing, food safety and quality, genetic engineering, environmental protection, agricultural biotechnology and more effective treatment of agricultural and municipal wastes provide a most impressive record of achievement (Jangid et al. 2011). The soil quality is the key to a sustainable agriculture. Understanding has shown that the transition from conventional agriculture to nature farming or organic farming can involve certain risks, such as initially lower yields and increased pest problems. Once through the transition period, which might take several years, most farmers find their new farming systems to be stable, productive, manageable and profitable without pesticides. Microorganisms are effective only when they are presented with suitable and optimum conditions for metabolizing their substrates including available water, oxygen, pH and temperature of their environment. Meanwhile, the various types of microbial cultures and inoculants available in the market today have rapidly increased because of these new technologies. Since microorganisms are useful in eliminating problems associated with the use of chemical fertilizers and pesticides, they are now widely applied in nature farming and organic agriculture (Higa, 1991; Parr et al 1994). Environmental pollution, caused by soil erosion and the associated transport of sediment, chemical fertilizers and pesticides to surface and groundwater and improper treatment of human and animal wastes has caused serious environmental and social problems throughout the world.

Often engineers have attempted to solve these problems using established chemical and physical methods. However, they have usually found that such problems cannot be solved without using microbial methods and technologies in coordination with agricultural production (Reganold et al., 1990).

The beneficial microorganisms are those that can fix atmospheric nitrogen, decompose organic wastes and residues, detoxify pesticides, suppress plant diseases and soil-borne pathogens, enhance nutrient cycling and produce bioactive compounds such as vitamins, hormones and enzymes that stimulate plant growth. Harmful microorganisms are those that can induce plant diseases, stimulate soil borne pathogens, immobilize nutrients and produce toxic and putrescent substances that adversely affect plant growth and health.

#### **Functions of Soil Microorganisms**

The soil microorganisms (actinomycetes, fungi, bacteria and cyanobacteria) so called soil microbial biomass are the agents of transformation of soil organic matter, nutrients and of most key soil processes. Their activities are much influenced by soil physico-chemical and ecological interactions. Many actinomycetes produce antibiotic compounds that kill other microorganisms *e.g.* streptomycin is produced by growing soil actinomycetes in pure culture. Bacteria (kingdom Monera) can be either autotrophic or heterotrophic and can be both aerobic and anaerobic. They have evolved mechanisms to adapt to life in the most extreme of environments. Due to their diversity they play many roles in the soil and are involved in all of the organic transactions. Cyanobacteria (formerly blue-green algae) belong to soil microflora and are either autotrophic or heterotrophic. They are also prokaryotic and among the most ancient of organisms. Many genera of cyanobacteria can fix atmospheric nitrogen *e.g.* *Anabaena* sp. and are especially plentiful in rice paddies and other wetland soils, where they fix large quantities of nitrogen. Soil bacteria are the primary digestive system of the soil. Their activity is responsible for almost 90% of all biological and chemical actions. The followings are the key function of beneficial soil microorganisms:

1. Transforming raw elements from one chemical form to another. Important nutrients in the soil are released by microbial activity are Nitrogen, Phosphorus, Sulphur, Iron and others,
2. Breaking down soil organic matter into a form useful to plants. This increases soil fertility by making nutrients available,
3. Degradation of pesticides and other chemicals found in the soil.
4. Suppression of soil born pathogen that causes diseases. The pathogens themselves are part of this group, but are highly outnumbered by beneficial microbes.
5. Fixation of atmospheric nitrogen,
6. Decomposition of organic wastes and residues,
7. Recycling and increased availability of plant nutrients,
8. Production of antibiotics and other bioactive compounds,
9. Production of simple organic molecules for plant uptake,
10. Complexation of heavy metals to limit plant uptake,
11. Solubilization of insoluble nutrient sources,
12. Production of polysaccharides to improve soil aggregation.

### Arbuscular Mycorrhizal Fungi (AMF)

The symbiotic association of plants and mycorrhizal fungi *i.e.* arbuscular mycorrhizal fungi, (AMF) has long been recognized for the benefits it provides with nutrient transport and uptake. However, there is considerable uncertainty about the functional benefits in intensive agricultural systems (Gupta et al., 2011). Even though AM symbiosis is widespread, the symbiotic functions of AMF species differ according to specific AMF isolates, host plants and soil properties. AMF associations are generally considered diffuse and non-specific because multiple species colonization linking together two or more plants is not uncommon (Selosse Marc-Andre et al. 2006; Smith et al., 2008). Identification of specific phylotypes of AMF and their relationship with soil properties is a crucial step to fully exploit the benefits from AMF (Selosse Marc-Andre et al. 2006). New knowledge on the microbial interactions in the mycosphere has the potential to enhance our ability to manipulate plant-mycorrhizal associations. A diverse array of bacteria *e.g.* *Pseudomonas*, *Bacillus*, actinomycetes and fungi *e.g.* *Aspergillus*, *Penicillium* species are capable of solubilising and mineralising plant unavailable forms of phosphorus in soils and the benefits from their use as inoculants are increasingly being recognized (Gyaneshwar, et al. 2002; Richardson, et al. 2011). The key function of arbuscular mycorrhizal fungi includes:

**i. Drought resistance:** AMF have long been implicated in improved host water relations by influencing everything from stomatal conductance, hydraulic conductance, and leaf and root hydration (Auge, 2001).

**ii. Mineralization of organic nutrients:** Recently, AMF have been shown to acquire N (Hodge et al. 2001) and P (Tarafdar and Marschener 1994) directly from decomposing sources, which was thought only to occur in saprobic fungi.

**iii. Seedling establishment:** The role of mycelial networks is thought to equalize resource allocation among neighboring plants, and a potential benefit may be that AM seedlings have access to more resources through the common mycelial network than do non-AM plants during the crucial establishment phase (van der Heijden et al. 2004).

**iv. Nutrient uptake:** AMF mycelia have been shown to increase uptake of many nutrients including P, N, S, B, Cu, K, Zn, Ca, Mg, Na, Mn, Fe, Al, and Si, along with trace elements (Clark and Zeto 2000). In some cases, AMF may be responsible for acquiring 100% of host nutrients *e.g.* P (Smith et al. 2004).

**v. Increased soil stability:** AMF greatly increases soil stability and weathering, possibly due to exudation of putative AMF protein glomalin, which is found in very high levels in AM soils (Rillig 2004).

**vi. Increased pollination:** AMF plants may also be more attractive to pollinators, due to their altered architecture and improved nutrient status (Wolfe et al. 2005).

**vii. Increased herbivore tolerance:** While AMF plants may be more appealing to herbivores, they have shown to increase tolerance to herbivory through increased compensatory response (Kula et al. 2005).

**viii. Pathogen resistance:** While AMF have yet to be developed for biological control, they appear to reduce disease symptoms for some plant diseases such as root rot, wilt, yellowing disease, and damping off (Whipps 2004).

**ix. Heavy metal tolerance:** AMF have shown to have differential sensitivities to soil metal toxicity, and may buffer hosts from toxic exposure, either through sequestration in the mycelium or by metabolizing it (Gaur and Adholyea 2004).

### **N<sub>2</sub> fixing Bacteria**

Symbiotic associations between legume plants and root-nodulating bacteria belong to the genera *Rhizobium*, *Bradyrhizobium*, *Ensifer* and *Mesorhizobium*. Nitrogen fixation is one of the essential beneficial biological processes for the economic and environmental sustainability of agriculture worldwide. Finding efficient rhizobia for the wide variety of legumes that are cultivated around the world and developing efficient management of symbioses in the field to realize approx 25 kg of N<sub>2</sub> fixation for each tonne of legume dry matter are the major challenges for the future. Diazotrophy, the ability to fix atmospheric nitrogen catalyzed by the enzyme nitrogenase, is distributed among diverse groups of bacteria and archaea (Reed *et al.* 2011).

Free living N<sub>2</sub> fixing bacteria *e.g.* *Azospirillum* sp., *Azotobacter* sp., *Acetobacter diazotrophicus*, *Herbaspirillum* spp., *Bacillus* sp., *Azoarcus* sp. are found in the rhizosphere and rhizoplane environments of cereal crops. Recent evidence not only identified new genera of N<sub>2</sub> fixing bacteria and archaea in natural and managed ecosystems but also indicated significant edaphic and environmental groupings in genetic diversity and functionality (Buckley *et al.* (2007). Non-rhizobial N<sub>2</sub> fixing bacteria can grow as endophytes in a number of grasses *e.g.* *Pseudomonas* species were the most dominant group of *nifH* carrying bacteria found in the rhizosphere of perennial native grasses (Gupta *et al.* 2011). The *nifH* gene is present in a number of non-Frankia actinobacteria like *Agromyces*, *Microbacterium*, *Corynebacterium* and *Micromonospora*.

### **Plant growth-promoting rhizobacteria (PGPR)**

The environmental benefits of using PGPR as microbial inoculants have been the reduction in the use of agricultural chemicals and its ecofriendly nature (Egamberdiyeva and Hoflich 2004). Free-living as well as symbiotic PGPR can improve plant nutrition and growth, plant competitiveness and responses to external stress factors (Mantelin and Touraine 2004). Mishra *et al.* (2010) reported that the PGPR were efficient for the seed germination and plant growth of *Cicer arietinum* under salinity and can be used as biofertilizer. Bacteria colonising roots that elicit shoot and root growth, referred generally as PGPR, are recommended (marketed) for improving plant growth and disease control both in agriculture and horticulture. PGPR can promote root and shoot growth either by producing plant hormones or secondary metabolites, controlling diseases, induction of systemic resistance or through changing physicochemical interactions with plants. Bacterial inoculants applied as biofertilisers are also being explored to alleviate stress from abiotic factors such as drought and salinity.

PGPR can promote the growth of plants using direct and indirect mechanisms. Direct mechanisms include lowering the production levels of ethylene through synthesis of 1-aminocyclopropane-1-carboxylate (ACC) deaminase in plants (Reed and Glick 2005; Safronova *et al.* 2006; Saleem *et al.* 2007); providing bioavailable phosphorus for plant uptake and atmospheric nitrogen fixation (Patten and Glick 1996) for plant use; sequestering trace elements like iron using siderophores (Glick 1995), *e.g.*, *Kluyvera ascorbata* SUD 165 that has the ability to synthesize the enzyme ACC deaminase protected *Brassica juncea* and *Brassica campestris* against Ni, Pb and Zn toxicity (Burd *et al.* 1998) by reducing the stress caused by high ethylene level; and production of plant hormones like gibberellins, IAA, cytokinins and auxins (Glick *et al.* 1999).

Root elongation of *Brassica napus* has also been shown to be stimulated by IAA synthesized by PGPR (Sheng and Xia 2006) as well as non-identified rhizobacteria on the *B. juncea* roots (Belimov et al. 2005). PGPR that indirectly enhance plant growth by suppressing phytopathogens do so by a variety of mechanisms. These include the ability to produce siderophores that chelate iron, making it unavailable to pathogens; synthesize antifungal metabolites such as antibiotics, fungal cell wall lysing enzymes, or hydrogen cyanide, which suppress the growth of fungal pathogens; successfully compete with pathogens for nutrients or specific niches on the root; and induce systemic resistance (Bloemberg and Lugtenberg 2001; Glick 1995; Persello-Cartieaux et al. 2003; Martinez-Viveros et al. 2010) (Table 1).

### **Endophytic Microorganisms**

Colonization traits usually relates to the bacterial traits involved in the entire plant-colonization process. In the interactive colonization processes, communication between the plant and microbe has a key role. Bacterial root colonization often starts with the recognition of specific compounds in the root exudates by the bacteria. These compounds probably also have major roles in below-ground community interactions. The plants simultaneously communicate with commensalistic, mutualistic, symbiotic and pathogenic microorganisms via compounds exuded by their roots (DeWeert et al. 2002; Bais et al. 2004; Bais et al. 2006). However, it has been suggested that plants can communicate to specifically attract microorganisms for their own ecological and evolutionary benefit (Compant et al. 2005). Owing to the complexity of the plant-microbe interactions in soil, it is extremely difficult to understand the detailed mechanisms involved in these putative selection processes. Rhizobium-plant interaction indicates the existence of highly evolved species specific communication systems (Bais et al. 2006) or from plant-*Pseudomonas* associations, in which two distinct plants have attracted specific minority strains of the *Pseudomonas sp.* involved, rather than the whole *Pseudomonas* community (Lemanceau et al. 1995). Much like the bacteria selected in the rhizosphere, particular endosphere bacteria might also be selected to establish residence inside plants. Bacterial traits required for effective root colonization are subject to phase variation, a regulatory process for DNA rearrangements orchestrated by site-specific recombinase. Endophytic population sizes are dependent on and positively correlated with, plant developmental stage, progressively increasing from the seedling stage onwards and reaching a maximum (Van Overbeek et al. 2008). The endophytic microorganisms can play a vital role in agricultural sustainability such as growth promoter, insect control, biopesticide, stress tolerance, etc.

**a. Endophytes as growth promoter:** There are numbers of mechanisms by which bacteria may promote plant growth and health which includes the production of plant growth phytohormones like auxins, cytokinins, gibberellins and ethylene, solubilised insoluble phosphate, produced HCN and siderophore and can fix atmospheric  $N_2$ . In symbiotic relationships, the microorganism helps the plant with nutrient assimilation or contributes biochemical activities that the plant lacks; microbes also confer a degree of protection against plant diseases. The plants supply competitive advantage to the corresponding microbes. Volatile substances such as 2-3 butanediol and acetoin produced by bacteria seem to be a newly discovered mechanism responsible for plant-growth promotion. Endophytes produce adenine ribosides that stimulate growth and mitigate browning of pine tissues (Smith and Read, 1996; Ryu et al. 2003; Pirttila et al. 2004).

**b. Endophytes for insect control:** The endophytic fungus *Phomopsis oblonga* was reported to protect elm trees against the beetle *Physocnemum brevilineum*. The capacity of endophytic fungus to repel insects, induce weight loss, growth and development reduction and even to increase pest death rate shown that the mode of action based on the capability to render the plant unpalatable to several types of pests like aphids, grasshoppers, beetles, etc. (Carroll *et al.* 1988). Alkaloids from *N. lolii* and *L. perenne* are capable of altering insect behaviour. Several of these alkaloids were added to the diet of adult individuals of Coleoptera *Heteronychus aratur*. Peramine, lolitrem B, lysergol-type alkaloids, festuclavine and lisergic acid showed no effects on the insect. Ergovine showed moderate effects whereas ergotamine, ergovaline from the ergot-type alkaloid family seem to be responsible for the plant resistance (Ball *et al.* 1997). Miles *et al.* (1998) showed that endophytic isolates of *Neotyphodium sp.* produce N-formilonine and a paxiline nalogous in the host *Echinopogum ovatus*. Dougherty *et al.* (1998) showed *Haematobia irritans* larvae of horn fly (cattle ectoparasite) killed when cattle manure was amended with seed extracts containing lolines from plants infected with *N. coenophialum*.

**c. Endophyte as biopesticidal:** Biopesticides, agent of biological origin, may be viruses, bacteria, pheromones, plant or animal compounds. The outstanding feature of biopesticides is environment friendly, easy biodegradability, faster rate of product development, low research expenditure, do not disturb natural biocenoses also application of biopreparation lowers the chemical loading to the environment, does not deteriorate the soil fertility, natural ways of decomposition in nature, non toxicity for warm-blooded organisms and overcoming the anti-environment chemical pesticide. *Burkholderia brasilensis* is an endophyte of roots, stems and leaves of sugarcane plant while *Burkholderia tropicalis* is confined to its roots and stems, with effective biopesticide properties. Many cultivated and wild type plants have been investigated for endophytic fungal metabolites which include guanidine and pyrrolizidine alkaloids, indole derivatives, sesquiterpenes, isocoumarin derivatives (Kumar *et al.* 2008).

**d. Tolerance to Environmental stress:** Endophytic microorganisms actively response to various biotic and abiotic stress factors that which hampers the overall agricultural scenario. Biotic stress tolerance mechanisms such as biocontrol of phytopathogens in the root zone through production of antifungal or antibacterial agents, pathogen antagonism, siderophore production aiding plant nutrition by iron chelation, phosphate solubilisation and induction of systematic acquired host resistance (Johansson *et al.* 2004). Endophytes from potato plants showed antagonistic activity against fungi and also inhibited bacterial pathogens belonging to the genera *Erwinia* and *Xanthomonas*. Some of the endophytic isolates produced in particular, various bacteria and fungi especially of the genera *pseudomonas*, *Bacillus* and *Trichoderma* produce a range of metabolites against other phytopathogenic fungi (Raaijmakers *et al.* 2002). Production of antibiotics sensitive to plant pathogens such as alkaloids, terpenoids, aromatic compounds, polypeptides and secretion of enzymes that has the capacity to hydrolyse compounds like cellulose, hemicellulose, chitin, proteins etc.

## VII. Cyanobacteria

The soils in desert and semi-arid regions have poor physical properties, low fertility and water deficiency. Cyanobacterial application to the organically poor semi-arid soil played a significant role in improving the status of carbon, nitrogen and other nutrients in the soil (Nisha *et al.*, 2007).

Organic matter content of dry land soils is chemically and biologically less stable and tends to decrease very rapidly in arid regions thus leading to poor organic matter contents. Poor soil structure usually associated with low organic carbon, compaction, salinity and sodicity results in reduced aeration and rates of water infiltration, hence more soil erodability and the reduced number and biodiversity of micro-flora ultimately has the adverse impact on plant growth and productivity. Flaibani et al. (1989) reported that exopolysaccharides from cyanobacteria also contribute to reclamation and improvement of desert soils. It is reported that cyanobacteria, as carbon and nitrogen fixers, can contribute to the improvement of soil nutrient status in arid soils (Jeffries et al., 1992; Lange et al., 1994). Cyanobacterial sheaths and EPS also play a major role in water retention due to their hygroscopic nature (Decho, 1990). The soil microflora contributes to increased water holding capacity of soils (Verrecchia et al., 1995). Belnap and Gillette, (1997) and Campbell, 1979; Belnap and Harper, (1995) reported that formation of algal crust by *Microcoleus vaginatus* and *M. chthonoplastes* in extremely dry climates, make significant contributions in stability of soils. It is reported that cyanobacteria produce extracellular polymeric substances (EPS) that help them to overcome conditions of water stress and also bind soil particles (Mazor et al., 1996). Marathe (1972) and Falchini et al., (1996) demonstrated that cyanobacteria play a very crucial role in bioamelioration of soils and enhancing crop yield not only aggregation initiation but also through protection of soil porosity due to reduction of the damaging effect of water addition. The diazotrophic cyanobacteria contribute substantially to the fertility of the soil especially under tropical paddy field conditions. Some native cyanobacterial strains have been reported to play an important role in improving soil aggregation, water holding capacity and soil aeration in paddy and several other agriculture fields (Rogers and Burns, 1994; DeCaire et al., 1997; Hegde et al., 1999). Better soil aggregation in cyanobacterial bio-fertilizer treated soils may be attributed to polysaccharides produced by the blue green algae (Ahmed et al., 2000). The native strains of cyanobacteria in semi-arid soils showed remarkable potential for improving structural stability, nutrient status and productivity of the soil due to their inherent tolerance capacity under limited soil moisture condition (Manchanda and Kaushik, 2000). Cyanobacteria produced organic matter, which increased soil organic C as well as water stable soil aggregates (Malamlssa et al., 2001). Cyanobacterial inoculations in disturbed soils have been reported to restore the population of carbon and nitrogen cycle microorganisms (Acea et al., 2003). Cyanobacteria seem to exert a mechanical effect on soil particles by the superficial network of the trichomes/filaments as well as enmeshing with soil particles at depth. Increase in total sugar content in soils having a cyanobacterial mat has been found to correspond to the enhanced soil aggregation process. The cyanobacterial consortium used as biofertilizer also produces abundant EPS about 25% of their total biomass (Nisha et al., 2007). Algal biomass and activity in soil crust are concentrated in the upper soil layers and EPS have gluing effect on soil particles leading to accelerates soil aggregation.

EPS produced by the cyanobacteria also seem to promote the activity of soil microflora as indicated by high soil enzymatic activities. Such microbial flora may produce more EPS, thus further amplifying the effect. Cyanobacteria play a very important role in fixing C and N in soil and have been considered very important for desert ecosystem. Removal of cyanobacteria from the arid sites reduces productivity and increases erosion by exposing unprotected subsurface soils to wind and water.

### VIII. Microorganisms for Bioremediation

Several chemicals are released into the soil ecosystem either as a method of disposal or as a consequence of the technology of their utilization. In particular, the application of pesticides, many of which are toxic or contain toxic contaminants, is central to the high yields in modern agriculture. With the advances in biotechnology, bioremediation has become one of the major developing research areas of environmental restoration, utilizing microorganisms to reduce the concentration/toxicity of various chemical pollutants such as heavy metals, dyes pesticides, etc. Biological treatment especially using cyanobacteria, for treatment of water bodies has manifold advantages over conventional methods, as cyanobacteria are cosmopolitan in environment and known to accumulate high levels of metal/pollutant; therefore, the process involved is relatively cheap and environment friendly. Systems are Cu, Zn, Ni, Co, Pb, Cr, Cd, etc. (Kaushik et al., 1999). Among the photoautotrophs, cyanobacteria are relatively more tolerant to heavy metals (Fiore and Trevors, 1994). The uptake of metal ions such as Cu, Pb, Zn, Ni, Cd, Cr, etc. has been reported in some of the efficient cyanobacteria are *Spirulina platensis*, *Oscillatoria angustissima*, *Microcystis sp.*, *Synechococcus sp.* (Verma and Singh, 1995; Rai et al., 1998; Pradhan and Rai, 2000; Yee et al., 2004).

The remediation of soils contaminated with heavy metals can be performed using chemical, physical and biological techniques. The metal and organic pollutants can be removed by the microbial flora. *Bacillus sp.* was very much efficient to remove the Au, Cd, Cr, Fe, Mn, Ni, Pb, U and Zn. It was recorded that *Bacillus sp.* can efficiently remove the metal pollutants from the waste or industrial effluents (Brierley and Brierley 1993; Philip et al. 2000; Gunasekaran et al. 2003). *Pseudomonas sp.* was also reported to Cu, Cr, Cd, Pb, Ni, U and Zn (Kapley et al. 1999; Sar and D'Souza 2001; Cybulski et al. 2003; Tarangini 2009). Ilhan et al., (2004) observed that *Staphylococcus saprophyticus* reduced Cr, Cu and Pb ions. The isolate was adsorbed 100% Pb ions at different pH range of 3-5 and at 27°C temperature. *Corynebacterium sp.* and *Flavobacterium sp.* were reported for removal of organic contaminants and halogenated hydrocarbons, phenoxyacetates and aromatic hydrocarbons (Jogdand, 1995). *Corynebacterium glutamicum* was able to reduce the thorium and uranium (Tarangini, 2009). The biosorption of heavy metal Cd and Cu by *Flavobacterium sp.* was reported by Rajbanshi, (2008) whereas, biosorption of Cu, Fe and Zn by *Corynebacterium sp.* was reported by Odokuma, (2009). Many investigators (Friis and Myers-Keith, 1986; Mattuschka et al., 1993; Jogdand, 1995; Tarangini 2009) reported that *Streptomyces sp.* can be used to remove the metal ions of Ag, Cd, Cu, Cr, Ni, Pb, U and Zn from the waste. *Streptomyces noursei* was able to reduce the metal ions in order Pb>Ag> Cu>Cr (Mattuschka et al., 1993). *Aspergillus niger* was reported to remove Ag, Au, Cd, Cu, Th, U and Zn (Townesley et al., 1986; Kuyucak and Volesky, 1988; Khalid et al., 1993; Guibal et al., 1995; Gunasekaran et al., 2003).

### IX. Plant Microbe Interaction

It is important to recognize that plants exist in intimate associations with microorganisms, some of which cause plant disease while others protect against disease. Identifying, understanding and utilizing microorganisms or microbial products to control plant disease and enhance crop production are integral parts of sustainable agriculture. Biological control has the potential to control crop diseases while causing no or minimal detrimental environmental impact. Some of the benefits of utilizing microorganisms include:

1. Reduced dependence on chemical pesticides, important because of the increasing restrictions on chemical usage due to environmental and public concerns,
2. Lack of development of pathogen resistance to biological control organisms, important due to the observed increase in resistance to many chemical controls,
3. Improvement of soil and enhancement of agricultural sustainability,
4. Selective action against specific groups of pathogens and not against beneficial organisms,
5. Biodegradability of microbial pesticides and the by-products of their manufacture.

The soil borne plant pathogens result in economic losses for farmers. For root diseases of mature crops, there are few effective and economical post-plant strategies for control. The use of chemical pesticides to control soil borne pathogens has caused significant changes in air and water quality, altered natural ecosystems resulting in direct and indirect effects on wildlife and caused human health problems e.g. methyl bromide, a fumigant used to control soil borne diseases, has become notorious in recent years for depleting the ozone layer and changing the climate of our planet. The future of sustainable agriculture will increasingly rely on the integration of biotechnology with traditional agricultural practices. Although genetic engineering promises enhanced yields and disease resistance, it is also important to recognize that plants exist in intimate associations with microorganisms, some of which cause plant disease while others protect against disease.

The probiotics, new concept of managing plant health through the manipulation of probiotic organisms associated with plants, has gained interest recently (Picard *et al.* 2008). Plant-specific stimulation of specific microbial groups in their rhizosphere suggests that plants may have evolved to strategically stimulate and support particular microbial groups capable of producing antibiotics as a defense against diseases caused by soil-borne pathogens (Weller *et al.* 2002). Soil bacteria belonging to the genus *Pseudomonas* are ubiquitous in most soils and have been linked to wide-ranging processes including plant growth promotion and inhibition, disease control, nutrient cycling, nitrogen fixation and bioremediation. Their ability to respond quickly to changes in physical, chemical, carbon and nutritional conditions in soil has been linked to their functional significance in agricultural ecosystems (Hornick 1992). Antibiosis is the most commonly suggested trait responsible for their activity against plant pathogens and a number of antimicrobial compounds have been identified e.g. 2,4-diacetylphloroglucinol (2,4-DAPG), phenazines (PHZ), pyrrolnitrin (PRN), pyoluteorin (PLT), hydrogen cyanide (HCN) and biosurfactant antibiotics (Picard *et al.* 2008). Conventional biochemistry-based characterisation of the chemicals is now complemented with molecular techniques e.g. metabolomics and transcriptomics, to unravel the mechanisms of production, interactions with pathogens and plants, genotypic and phenotypic diversity of organisms capable of producing similar compounds and determine their activity in natural soil environments.

#### **X. Biological control organisms**

The bacteria, fungi and actinobacteria can act as biocontrol agents against root diseases (Whipps, 2001). A number of bacterial and fungal inoculant formulations are available commercially to control diseases in agricultural and horticultural crops (Westerdijk 2000). The success of biocontrol inoculants depends upon the ability to:

- a. Lengthen the period, during which a threshold population density is sustained in the rhizosphere,

- b. Maintain the adequate populations needed to provide effective biological control,
- c. Increase the magnitude of disease control provided by introduced rhizobacteria.

The cyanobacteria can also be used as biocontrol agents based on previous research. In modern agriculture practices, the conventional control methods of plant diseases have not been found quite efficient due to survival of the reproductive structures of pathogens in the soil. At the same time, fungicides and other artificial chemical agents inhibit the growth and development of crop plants (Nyporko et al., 2002). Various antagonistic microorganisms have been identified for almost every life cycle stage of several plant pathogenic microbes and cyanobacteria it is here that are as the efficient antagonistic agents against several pathogenic microbes (Yuen et al., 1994). Various investigators have proved that cyanobacteria can be efficiently used as biocontrol agent (DeCaire et al., 1990; DeMule et al. 1991; Teuscher et al., 1992; Zulpa et al., 2003; Tassara et al. 2008). Biological control is an attractive approach for the control of soil borne diseases (Cook, 1993). Actinobacterial endophytes can colonise plants without disrupting the normal endophytic populations, can produce antifungal antibiotics and plant growth hormones and can also induce systemic disease resistance in plants (Conn *et al.* 2008).

Advantages of a biological approach to disease control include a lack of environmental damage, reduced human health risks, lack of resistance development in the pathogen, selectivity in mode of action, lack of activity against most beneficial microorganisms and improved soil conditions and agricultural sustainability. Biocontrol inoculants are generally tested for their antibiosis potential due to antagonism, hyper-parasitism, competition and predation by indigenous organisms; however, organisms that induce a systemic resistance to diseases and pests have the greatest potential to succeed under field conditions (Kloepper *et al.* 2004). Some soils can suppress the severity of disease even in the presence of a pathogen, host plant and favourable climatic conditions for the disease. There are a number of examples, both in Australia and worldwide, where agricultural soils have become suppressive to soil-borne pathogens (Weller *et al.* 2002; Cook, 2007; Gupta, *et al.* 2011).

## CONCLUSION

Soil microbes especially bacteria and fungi are essential for decomposing organic matter and recycling old plant material. Microbes in terrestrial environments are important catalysts of global carbon and nitrogen cycles, including the production and consumption of greenhouse gases in soil. Some microbes produce the greenhouse gases carbon dioxide (CO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O) while decomposing organic matter in soil. Others consume methane (CH<sub>4</sub>) from the atmosphere, thus helping to mitigate climate change. The importance of each of these processes is influenced by human activities and impacts the warming potential of Earth's atmosphere. The soil quality is the key to a sustainable agriculture. The symbiotic association of plants and mycorrhizal fungi *i.e.* arbuscular mycorrhizal fungi, (AMF) has long been recognized for the benefits it provides with nutrient transport and uptake.

Nitrogen fixation is one of the essential beneficial biological processes for the economic and environmental sustainability of agriculture worldwide. Free-living as well as symbiotic PGPR can improve plant nutrition and growth, plant competitiveness and responses to external stress factors. PGPR can promote the growth of plants using direct and indirect mechanisms.

The endophytic microorganisms can play a vital role in agricultural sustainability such as growth promoter, insect control, biopesticide, stress tolerance, etc. Cyanobacteria seem to exert a mechanical effect on soil particles by the superficial network of the trichomes/filaments as well as enmeshing with soil particles at depth. The cyanobacterial consortium used as biofertilizer also produces abundant EPS. With the advances in biotechnology, bioremediation has become one of the major developing research area of environmental restoration, utilizing microorganisms to reduce the concentration/toxicity of various chemical pollutants such as heavy metals, dyes pesticides, etc. It is important to recognize that plants exist in intimate associations with microorganisms, some of which cause plant disease while others protect against disease. Identifying, understanding and utilizing microorganisms or microbial products to control plant disease and enhance crop production are integral parts of sustainable agriculture. Biological control has the potential to control crop diseases while causing no or minimal detrimental environmental impact. The competent soil microorganisms can be used in various ways to sustain our agriculture practices.

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