Utilizing Beneficial Microorganisms for Sustainable Crop Production

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Sustainable agriculture plays a crucial role in addressing the agricultural demands of today's world, offering solutions that conventional farming often fails to achieve. This approach leverages farming techniques that fully utilize environmental resources while ensuring environmental safety, resulting in eco-friendly and healthy agricultural products. Microbial populations are fundamental to the processes that enhance the strength and productivity of agro-ecosystems. Numerous studies have improved our understanding of the diversity, dynamics, and importance of soil microbial communities and their beneficial roles in agricultural productivity. This review focuses on the contributions of plant growth-promoting rhizobacteria (PGPR) and cyanobacteria to sustainable agriculture. An ideal agricultural system should be sustainable, enhance human health, benefit the environment, and produce sufficient food for the growing global population. The use of biofertilizers can reduce the reliance on urea, prevent soil organic matter depletion, and significantly lower environmental pollution. Cyanobacteria and PGPR serve as excellent model systems, providing biotechnologists with novel genetic materials and bioactive compounds for various agricultural and environmental applications. These microorganisms offer an environmentally sustainable approach to enhancing crop production and soil health.

Key Words: Sustainable agriculture. Plant growth-promoting rhizobacteria (PGPR), Cyanobacteria, Crop production, Soil microbial communities

Introduction

Sustainable agriculture is a comprehensive concept rather than a specific methodology. It encompasses advancements in agricultural management practices and technology, reflecting a growing recognition that conventional agriculture developed post-Green Revolution will not suffice to meet the needs of the burgeoning population in the 21st century (Ram et al., 2018). Conventional agriculture is experiencing either decreased production or increased costs, or both. Monoculture farming, such as repeated wheat cultivation on the same land, leads to the depletion of topsoil, soil vitality, groundwater purity, and beneficial microbes and insects, making crops vulnerable to parasites and pathogens. The escalating need for fertilizers and pesticides, along with rising energy demands for tilling to aerate soils and increased irrigation costs, are major concerns. While conventional methods initially enabled substantial increases in crop yields and profits, they have failed to be sustainable for the future. The rise of corporate farming, driven primarily by profit, has destabilized rural communities and accelerated detrimental effects on both farmland ecology and neighboring natural environments. Cost-cutting measures often target farm workers, significantly degrading their financial rewards compared to other sectors, which lowers their standard of living and impacts the economic viability of small rural towns. Urban expansion and the growth of business and industrial complexes have reduced available farmland. Prime farmland is increasingly becoming valuable real estate for high-end residential developments, and economically, farming cannot compete. The profits from converting farmland into residential subdivisions are far greater than those from farming (Keswani 2015).

In the past century, the industrialization of agriculture has significantly increased productivity, leading to an abundance of food for the general population. However, this has also caused serious environmental and social issues that need urgent solutions. Therefore, a shift towards more environmentally sustainable agriculture that preserves ecosystems and biodiversity is essential. One potential solution to reduce the environmental impact of chemical fertilizers, herbicides, and pesticides is the use of plant growth-promoting rhizobacteria (PGPR). This term, first defined by Kloepper and Schroth in 1978, describes soil bacteria that colonize the rhizosphere of plants, promoting growth through various mechanisms. Since then, research has increasingly focused on understanding these bacteria's positive (or negative) effects, with numerous reports published.

Initially, rhizobacteria were screened for in vitro production of phytohormones like auxins, siderophores, phosphorus solubilization, or nitrogen-fixing to identify PGPR from the rhizosphere and assess their growth-promoting activity under axenic conditions. Promising PGPR candidates were then used as inoculants for plants in natural conditions in pots and field trials. PGPR application in legumes has mainly focused on manipulating rhizobia to enhance legume growth and development through nodulation and nitrogen fixation, as many soil-borne rhizobia species can establish symbiosis with legumes, making them the best-known beneficial plant-associated bacteria and the most important biofertilizers (Singh et al., 2014).

Benefits to plants from host–PGPR interactions include improved health and growth, disease suppression, and accelerated nutrient availability and assimilation. These benefits can be achieved directly through PGPR-host interactions or indirectly through antagonistic activity against plant pathogens (Filippi et al., 2011; Keswani et al., 2014; Singh et al., 2019). Direct stimulation involves mechanisms like ACC-deaminase production to reduce ethylene levels in roots, production of plant growth regulators (auxins, gibberellins, cytokinins), symbiotic nitrogen fixation, and solubilization of minerals like phosphorus. Indirect stimulation involves biocontrol through antagonistic activity against phytopathogens, inducing plant systemic resistance, and interfering with bacterial quorum sensing systems. Some reports suggest that PGPR may use multiple mechanisms to enhance plant growth (Krey et al., 2013; Tajini et al., 2012; Yasmin et al., 2004). Different PGPRs can be applied to crops through commercially available formulations, and the popularity of microbial inoculants has increased due to extensive research that has improved their effectiveness and consistency. Microbial inoculants include three major groups: arbuscular mycorrhizal fungi (AMF), PGPR, and symbiotic-nitrogen-fixing rhizobia, with each group's beneficial capacity studied separately (Bisen et al., 2015; Fraceto et al., 2018; Keswani et al., 2016).

Moreover, numerous studies are evaluating the effects of different microbial combinations or consortia, such as AMF–PGPR and symbiotic-nitrogen-fixing rhizobia. Understanding the mechanisms of plant growth promotion is crucial to deciding which microorganism to use with which plant in a given situation. The rhizosphere, the soil zone surrounding a plant root, is influenced by the roots' biology and chemistry. Root exudates include amino acids, organic acids, carbohydrates, sugars, mucilage, and proteins, and rhizobacteria's ability to use these organic acids as carbon sources correlates with rhizosphere competence (Bosco et al., 2017; Singh et al., 2016b). The structure of the rhizobacterial community is determined by the plant species, as differences in root exudate composition and amounts likely affect microbial populations. Understanding how plant roots select soil microbes to form the rhizosphere's microbial community is important for using rhizobacteria as plant growth promoters. This review describes the mechanisms used by these bacteria to enhance plant growth and agronomic parameters, and summarizes the current progress of using PGPR on major cereal crops like maize, rice, and wheat, as well as legumes such as soybean and dry beans.

The contributions of soil micro-flora in sustainable agricultural production

A significant transformation is occurring globally in agricultural practices and food production. Historically, the primary objective was to maximize the yield potential of food crops and their productivity. Today, this pursuit of productivity is increasingly coupled with a strong emphasis on sustainability. Sustainable agriculture involves the effective management of agricultural resources to meet human needs while preserving environmental quality and conserving natural resources for future generations. Enhancing agricultural sustainability necessitates the optimal use and management of soil fertility and its physico-chemical properties, both of which depend on soil biological processes and biodiversity. This entails adopting management practices that boost soil biological activity, thereby enhancing long-term soil productivity and crop health. These practices are crucial in marginal lands to prevent degradation, restore degraded lands, and in regions where high external input agriculture is not feasible.

Over the past 50 years, microorganisms have played a pivotal role in advancing medical technology, improving human and animal health, enhancing food processing, safety, and quality, facilitating genetic engineering, protecting the environment, advancing agricultural biotechnology, and improving the treatment of agricultural and municipal wastes. Much ecological advancement would have been unattainable through conventional chemical and physical engineering methods alone, or if possible, they would not have been practically or economically viable. While microbial technologies have been successfully applied to various agricultural and environmental challenges in recent years, they have not gained widespread acceptance within the scientific community due to the difficulty in consistently reproducing their beneficial effects. Microorganisms are only effective when provided with optimal conditions for metabolism, including adequate water, oxygen, pH, and ambient temperature. The types of microbial cultures and inoculants available in the market have proliferated rapidly due to new technologies, with significant achievements being made in systems where technical guidance is coordinated with the marketing of microbial products (Keswani 2015; Singh et al., 2016).

Microorganisms, useful in addressing issues related to chemical fertilizers and pesticides, are now widely applied in agriculture. Environmental pollution, caused by excessive soil erosion and the resultant transport of sediment, chemical fertilizers, and pesticides to surface and groundwater, along with ineffective treatment of human and animal wastes, poses serious environmental and social problems globally. While engineers have attempted to solve these problems using established chemical and physical methods, they have found that these issues cannot be resolved without employing microbial methods and technologies. Soil microorganisms interact with plant systems, with many microbes colonizing roots, forming biofilms or mantles, and inducing systemic resistance during pest attacks. Many of these microbes have the ability to solubilize or mobilize mineral elements and produce growth-promoting substances that enhance plant health. The use of biofertilizers not only fixes atmospheric nitrogen and solubilizes mineral nutrients but also helps in maintaining soil health, preserving soil fertility, and ensuring the quality of crop products.

Role of phosphate solubilising microorganism in sustainable agriculture

Microorganisms play a crucial role in soil health, directly or indirectly influencing it through their beneficial or detrimental activities. Rhizospheric microorganisms are key mediators of soil processes such as decomposition, nutrient mobilization and mineralization, nutrient and water storage and release, nitrogen fixation, and denitrification. Additionally, organisms with phosphate-solubilizing abilities can convert insoluble phosphatic compounds into soluble forms, making them available to crops. The role of rhizospheric organisms in mineral phosphate solubilization has long been recognized, prompting extensive studies on this process facilitated by naturally abundant rhizospheric microorganisms. Notable genera of mineral phosphate solubilizers include Bacillus and Pseudomonas, with Aspergillus and Penicillium also demonstrating significant activity (Dhankhar et al., 2013).

For instance, the nematophagous fungus *Arthrobotrys oligospora* has been tested both in vitro and in vivo for its ability to solubilize various types of rock phosphates. The fungus successfully solubilized phosphates from these rocks in vivo, highlighting its potential in agricultural applications. While much research has focused on biological nitrogen fixation through the use of microorganisms as biofertilizers, fundamental studies on phosphate solubilization by nodule bacteria have been less extensive. However, it is well established that phosphorus availability is a critical factor for effective nitrogen fixation in Rhizobium-legume symbiosis. There are relatively few reports on phosphate solubilization by *Rhizobium* and the non-symbiotic nitrogen fixer *Azotobacter* (Baliah et al., 2016).

Phosphate-solubilizing microorganisms (PSM) are ubiquitous, though their populations vary between different soils. In soil, phosphate-solubilizing bacteria typically make up 1–50% of the total bacterial population, while phosphate-solubilizing fungi constitute 0.5%–0.1% of the total fungal population. Generally, phosphate-solubilizing bacteria outnumber their fungal counterparts by a factor of 2–150. A high concentration of PSM is found in the rhizosphere, where they are more metabolically active compared to those from non-rhizospheric sources. Interestingly, salt, pH, and temperature-tolerant phosphate-solubilizing bacteria are most abundant in the rhizoplane, followed by the rhizosphere and root-free soil in alkaline soils. These stress-tolerant PSM strains serve as excellent models for studying the physiological, biochemical, and molecular mechanisms of phosphate solubilization under stressed ecosystems. It has also been observed that phosphate-solubilizing bacteria may lose their solubilizing activity upon repeated sub-culturing, a phenomenon not noted in phosphate-solubilizing fungi (Halder et al., 1991; Abd-Alla, 1994; Chabot et al., 1996).

Phosphate-solubilizing fungi generally produce more acids and, consequently, exhibit greater phosphate solubilization activity than bacteria in both liquid and solid media. The solubilization ability of PSM is influenced by the nature of the nitrogen source in the media, with higher solubilization rates observed in the presence of ammonium salts compared to nitrate. This is attributed to the extrusion of protons to balance ammonium uptake, leading to a decreased extracellular pH. However, in some cases, ammonium can also lead to a decrease in phosphorus solubilization.

Soil microbes for sustainable agriculture and environment

Agriculture, in a broad sense, involves the integration of various agro-ecological factors and production inputs by farmers to achieve optimal crop and livestock production. Thus, it is logical to assume that farmers should be interested in managing beneficial soil microorganisms, which are crucial components of the agricultural environment. However, this notion is often rejected by naturalists and advocates of nature farming and organic agriculture. They argue that beneficial soil microorganisms will naturally proliferate with the addition of organic amendments to the soil, providing carbon, energy, and nutrient sources. This might be true in small-scale farming where there is an abundance of organic materials for recycling.

In most scenarios, however, both beneficial and harmful soil microorganisms have been advantageously managed when crops are cultivated in various agro-ecological zones, often through crop rotations and without the use of pesticides. This has led scientists to explore the use of efficient microorganisms as soil and plant inoculants to shift the microbiological balance in favor of enhanced soil quality and eco-friendly agriculture. Low agricultural production efficiency is often linked to poor energy conversion coordination, which is influenced by crop physiological factors, environmental conditions, and biological factors, including soil microbes. The soil and rhizosphere microflora can promote plant growth and enhance their resistance to pathogens and harmful insects by producing bioactive metabolites. These microorganisms play a critical role in maintaining plant growth, thereby affecting both soil and crop quality.

There is a broad range of benefits that can be realized depending on the predominance and activity of these microorganisms at any given time. Increasingly, there is a consensus that achieving maximum economic agronomic yields of high quality at higher net returns is possible without relying on artificial fertilizers, herbicides, insecticides, and pesticides. This was not considered a likely possibility with conventional agricultural practices until recently. However, it is now recognized that the best soil and agricultural management practices aimed at achieving sustainable and environmentally friendly agriculture also promote the growth, number, and activity of efficient soil microflora. This, in turn, enhances the growth, yield, and quality of agricultural crops. Essentially, healthy, living soil with improved quality forms the foundation of future sustainable agriculture.

Agricultural productivity and plant growth promoting rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) broadly include N2-fixing rhizobacteria that colonize the rhizosphere, providing nitrogen to plants, in addition to the well-known legume-rhizobia symbioses. For PGPR to promote plant growth, they must colonize the rhizosphere around the roots, the rhizoplane (root surface), or within the root tissues themselves. PGPR can influence plant growth both indirectly and directly. Indirect promotion occurs when PGPR mitigate or antagonize the harmful effects of one or more phytopathogens. Direct promotion involves either supplying plants with compounds synthesized by the bacteria or facilitating the uptake of nutrients, enhancing various growth parameters and yields of crops and fruits.

Among the diverse bacteria identified as PGPR, Bacillus and Pseudomonas are predominant. PGPR directly influence plant growth through the production of phytohormones, solubilization of inorganic phosphates, and increased iron nutrition via iron-chelating siderophores, as well as the emission of volatile compounds that affect plant signaling pathways. Additionally, through mechanisms such as antibiosis, competition for space and nutrients, and induction of systemic resistance in plants against a wide range of root and foliar pathogens, PGPR reduce the populations of root pathogens and other harmful microorganisms in the rhizosphere, thereby benefiting plant growth (Table 1).

Crop parameters	**PGPR**
Direct growth promotion of mustard and cabbage	*R. leguminosarum*
Early developments of rice seedlings	*P. putida* G 12–2
Growth of rice and sugarcane plants	*Azospirillum brasilense* and *A. irakense*
Growth of bajra	*P. fluorescens*
Growth stimulation of *Solanum lycopersicum*	*P. putida*
Growth and productivity of rice	*Azotobacter* and *Azospirillum*
Enhance uptake of N, P and K in nutrient deficient soil by field pea	*P. alcaligenes*, *B. polymyxa*, and *Mycobacterium phlei*
Stimulates growth and yield of chick pea	*Pseudomonas*, *Azotobacter* and *Azospirillum*
Improve phosphorus uptake in wheat	*R. leguminismarum* and *Pseudomonas*
Improves seed germination and yield of maize	*P. putida*

Plant growth promoting rhizobacteria in plant production

According to the FAO, after sugarcane, the next three leading crops in terms of production (in million tonnes) globally are maize, rice, and wheat. The worldwide production of maize exceeded 853 million tonnes. By 2050, the demand for maize in developing countries is projected to double. In the same year, global rice production was nearly 723 million tonnes. Rice is highly adaptable to different environments, making it the most widespread crop globally. It can grow in drought conditions or in shallow water (up to 50 cm), across a wide range of latitudes, and at altitudes up to 3000 meters. Due to these characteristics, the FAO considers rice a strategic crop for global food security.

Regarding wheat, the global production in 2011 was approximately 710 million tonnes. Wheat serves as a major renewable resource for food, feed, and industrial raw materials, and it is the most widely cultivated crop in the world. Despite significant yield increases throughout the last century, wheat yields began to plateau in 1995, with growth stagnating in nearly every country. This stagnation has been linked to the increasing frequency of adverse climatic conditions, such as spring droughts during stem elongation and heat stress around flowering and grain filling periods.

During the same period, the global population rose from 5.7 billion to 6.3 billion and is expected to exceed 9.5 billion by 2050. The demand for wheat in developing countries is anticipated to increase by 62% by 2050, while climate change is projected to reduce production in these regions by 28%. Soybean is another crucial crop, especially in developing countries, where it often forms a significant part of the human diet. Soybeans and soy-products are essential in some regions. They are rich in isoflavones, high-quality protein, low in saturated fats, and high in dietary fiber. Similarly, beans are vital for human diets, particularly in developing nations, providing essential proteins, vitamins (like folate), and minerals (such as Ca, Cu, Fe, Mg, Mn, Zn). In developed countries, the health benefits of beans, including their role in preventing diseases like cancer, diabetes, and heart disease, are well recognized (Brisson et al., 2010; Lobell et al., 2011).

Annual production of beans, including both dry and snap beans, exceeds 21 million tonnes, accounting for more than half of the world's total legume food production. Given these data, it is evident that using plant growth-promoting rhizobacteria (PGPR) as inoculants could offer significant benefits. PGPR represents a biological alternative for the sustainable production of these vital crops, enhancing growth and yield while promoting environmental sustainability.

Role of cyanobacteria in agriculture and environmental sustainability

Due to their evolutionary antiquity, cyanobacteria have adapted to survive in a variety of extreme environments, including drought, salinity, and temperature fluctuations. Throughout their phylogenetic history, cyanobacteria have been exposed to numerous stresses, particularly water and salt stress. They are especially well-adapted to drought and desiccation, likely due to the presence of specialized vegetative cells, such as spores or akinetes, which are resistant to desiccation.

Cyanobacteria represent a renewable biomass source that releases soluble organic substances into the environment as extracellular products, also known as secondary metabolites. These metabolites can be mineralized by microflora, benefiting agricultural crops. These substances can act as growth promoters or inhibitors for various organisms, including soil microflora. Cyanobacteria have been reported as effective biocontrol agents against plant pathogens, although observations of their effects on other plant pathogens under field conditions are limited (Singh et al., 1997; Earanna and Govindan 2002).

Cyanobacteria in chronically contaminated environments (with salts, heavy metals, pesticides, and other potential toxicants) tend to absorb and accumulate these toxicants intracellularly, making them useful indicators of pollution. As primary producers in diverse ecosystems, their tolerance to extreme environments (salinity, drought, contaminated soils) is ecologically significant. However, the mechanisms underlying their adaptations to such conditions are not well understood, necessitating further investigation to predict their role in restoring wastelands for sustainable agriculture.

Using indigenous cyanobacterial strains as biofertilizers can enhance the physico-chemical and biological properties of the soil, promoting the yield of crops such as rice, wheat, and pearl millet under saline, drought, and contaminated agro-ecosystems. Regular application of cyanobacteria adapted to extreme environments holds promise for wasteland management, soil stability, nutrient status improvement, soil microbial activity enhancement, nutrient mineralization, and crop growth in an ecologically sustainable manner.

Cyanobacterial biofertilizers mobilize essential nutrients like phosphorus (P) from non-usable to usable forms through biological processes. They play a crucial role in various soil chemical transformations, influencing the bioavailability of major nutrients to plants. Cyanobacteria and phosphate-solubilizing bacteria (PSB) have been used to enhance crop production by increasing the availability of P.

In recent years, biofertilizers have become an integral part of the integrated nutrient supply system in Indian agriculture. The ability of cyanobacteria to mobilize insoluble inorganic phosphorus was demonstrated by Kleiner and Harper (1977), who found more extractable P in soils with cyanobacterial cover compared to nearby soils without cover. Synergistic effects of efficient soil microbes and cyanobacteria, including the excretion of organic acids to increase P availability and the reduction of sulphide injury through increased oxygen content, have also been reported.

The success of biotechnology tools, such as cyanobacterial biofertilizer technology, largely depends on cost-effectiveness and simplicity. One biotechnological application involves producing and distributing cyanobacterial biofertilizers to farmers. Instead of expensive glass containers, plastic bottles, polyethylene, and polypropylene sachets are used for distributing liquid cyanobacterial cultures. This technology allows farmers to generate biofertilizers on their own with minimal additional inputs once they obtain the soil-based starter culture. However, the outdoor cyanobacterial production technique is not widely popular among farmers.

The utilization of cyanobacterial biofertilizers is also limited due to a lack of basic knowledge regarding the factors that influence the success or failure of inoculated cyanobacterial species. Detailed field investigations are needed to develop efficient, high-quality cyanobacterial soil inoculums and their application in specific regions such as saline and drought-prone areas. Despite its potential, the use of cyanobacterial biofertilizer technology remains limited, underscoring the need to introduce cyanobacterial applications under field conditions for sustainable agriculture.

Cyanobacteria in stability and productivity of desert soils

Dryland soils in desert and semi-arid regions face significant challenges, including poor physical properties, low fertility, and water scarcity. The organic matter in these soils is often chemically and biologically unstable, depleting rapidly in arid regions and leading to low organic content (Nisha et al., 2007). Poor soil structure, typically associated with low organic carbon, compaction, salinity, and sodicity, results in reduced aeration and water infiltration rates, increased soil erosion, and decreased microflora biodiversity, which adversely affects plant growth and productivity. Applying cyanobacteria to nutrient-deficient semi-arid soils has shown significant improvements in the levels of carbon, nitrogen, and other essential nutrients. The high organic carbon content in treated soils is attributed to the autotrophic nature of cyanobacteria, which synthesize and add organic matter to the soil. Diazotrophic cyanobacteria, which are both photoautotrophic and N2-fixing, enhance crop production by increasing the carbon and nitrogen status of soils. Biogenic soil crusts, primarily composed of cyanobacteria, have been found to increase soil fertility by incorporating organic matter into the soil. Recent studies indicate that cyanobacterial crusts contribute significantly to arid and semi-arid ecosystems by adding carbon and nitrogen, along with several micronutrients, thus improving soil hydrology and stability (Orlovsky et al., 2004). Cyanobacterial inoculations have been reported to restore the population of carbon and nitrogen cycle microorganisms in disturbed soils (Acea et al., 2003).

Cyanobacteria produce extracellular polymeric substances (EPS) that help them withstand water stress and bind soil particles. Their sheaths and EPS play a crucial role in water retention due to their hygroscopic nature, thus enhancing the soil's water-holding capacity. As both carbon and nitrogen fixers, cyanobacteria improve soil nutrient status in arid regions. Research by Flaibani et al. (1989) demonstrated that exopolysaccharides from cyanobacteria aid in reclaiming and improving desert soils. Cyanobacteria also mechanically affect soil particles through their trichomes/filaments and enmesh soil particles at depth, improving soil aggregation, water-holding capacity, and aeration in paddy fields and other agricultural settings.

Numerous studies have shown that cyanobacteria are crucial in soil bioamelioration, enhancing crop yields by initiating soil aggregation and protecting soil porosity from the detrimental effects of water addition (Ramirez et al. 2011). Diazotrophic cyanobacteria significantly contribute to soil fertility, especially in tropical paddy fields. However, there is limited information about their role in other crops in semi-arid areas where water availability constraints prevent paddy cultivation. Native cyanobacterial strains in semi-arid soils have shown remarkable potential for improving soil structural stability, nutrient status, and productivity due to their tolerance of limited soil moisture conditions.

The enhanced soil aggregation in treated soils is attributed to the polysaccharides produced by blue-green algae. Studies have found that increased soil sugar content correlates with improved soil aggregation. Cyanobacterial biofertilizers also produce abundant EPS, comprising about 25% of their total biomass, which helps glue soil particles together, accelerating soil aggregation. EPS also promotes soil microflora activity, which in turn produces more EPS, amplifying the effect (Hagemann et al. 2015). Cyanobacteria play a crucial role in fixing carbon and nitrogen in soil, essential for desert ecosystems. Their removal from arid sites reduces productivity and increases erosion by exposing unprotected subsurface soils to wind and water. Algal crust formation by species like *Microcoleus vaginatus* and *M. chthonoplastes* in extremely dry climates significantly contributes to soil stability.

These findings suggest that applying drought-resistant indigenous cyanobacterial biofertilizers at relatively high doses can improve the physico-chemical and biological properties of soil and promote crop yield under drought and water-limited conditions. Such applications are predicted to be crucial for enhancing soil quality, nutrient status, microflora, nutrient mineralization, and crop growth in desert and semi-arid soils sustainably. Understanding the biology of drought-resistant cyanobacteria could be beneficial for sustainable agriculture, particularly for drought-tolerant crops. The tolerance of cyanobacterial strains to osmotic stress makes them effective for agriculture in arid and semi-arid regions where water scarcity is a significant challenge. Adapted cyanobacterial strains to high osmotic stress conditions could be a viable strategy for enhancing crop productivity and reclaiming wastelands for sustainable agriculture.

PGPR as biofertilizers

A group of biofertilizers includes beneficial rhizobacteria identified as Plant Growth-Promoting Rhizobacteria (PGPR), comprising strains from genera such as *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholdaria*, *Enterobacter*, *Rhizobium*, *Erwinia*, and *Flavobacterium* (Rodriguez and Fraga, 1999). Free-living PGPR have shown promise as biofertilizers, with numerous studies indicating that PGPR inoculations can promote plant growth, increase yield, and enhance the uptake of nitrogen (N) and other elements. Additionally, PGPR treatments stimulate root growth, resulting in a root system with a larger surface area and more root hairs

(Sheng and He 2006; Glick et al., 2007). Typically, large quantities of artificial fertilizers are used to replenish soil nitrogen (N) and phosphorus (P), which is costly and poses environmental risks. Most P in soil exists in insoluble compounds that are not available to plants. N2-fixing and P-solubilizing bacteria (PSB) are crucial for crop plants as they enhance N and P uptake, playing a significant role as PGPR in biofertilization. The use of these microbes as eco-friendly biofertilizers can reduce the reliance on expensive phosphatic fertilizers. Biofertilizers increase the availability of accumulated P through solubilization, improve the efficiency of biological N2-fixation, and boost the availability of elements like Fe and Zn due to the generation of plant growth-promoting substances. Inoculation with both N2-fixing and P-solubilizing bacteria has been found to be more effective than single microbe inoculations, providing more balanced nutrition to crops such as sorghum, barley, blackgram, soybean, and wheat (Alagawadi and Gaur 1992; Belimov et al., 1995; Abdalla and Omer 2001; Tanwar et al., 2002; Galal 2003)..

Reports on the co-inoculation of *Rhizobium* and PSB in wheat are rare, particularly in India, where limited research has been conducted. Therefore, extensive investigations into the effects of single and dual inoculations of N2-fixing and P-solubilizing bacterial species on crop yields are urgently needed. Recent findings indicate that treating arable soils with PGPR inoculations significantly enhances agronomic yields. The PGPR strains *Pseudomonas alcaligenes* PsA15, *Bacillus polymyxa* BcP26, and *Mycobacterium phlei* MbP18 have shown pronounced stimulatory effects on plant growth and the uptake of N, P, and K by maize in nutrient-deficient calcisol soils. The enhancement in agronomic yields by PGPR is attributed to the production of growth-promoting phytohormones, phosphate mobilization, siderophore and antibiotic production, inhibition of plant ethylene synthesis, and induction of plant systemic resistance to pathogens (Han et al., 2004; Zahir et al., 2004; Ramazan et al., 2005;).

Furthermore, a study by Kavino et al. (2010) reported that the strain *Pseudomonas fluorescens*, combined with chitin, increased growth, leaf nutrient content, and yield of banana plants under perennial cropping systems. This suggests that, in light of environmental issues related to the excessive use and high production costs of fertilizers, PGPR could be an effective and sustainable alternative for eco-friendly agriculture.

PGPR in saline agricultural soils

Soil salinity presents a significant challenge for vegetable and other crops, particularly in arid and semiarid regions, where it suppresses plant growth by altering plant physiology and nutrient uptake. Pseudomonas species have garnered significant attention among soil-borne bacteria due to their versatile metabolism, efficient root colonization abilities, and capacity to produce various enzymes and metabolites that aid plants in withstanding diverse biotic and abiotic stresses. Plant Growth-Promoting Rhizobacteria (PGPR) indirectly facilitate plant growth by reducing plant pathogens and directly by enhancing nutrient uptake through the production of phytohormones (e.g., auxin, cytokinin, and gibberellins), enzymatically lowering plant ethylene levels, and producing siderophores.

Research has shown that inoculations with Arbuscular Mycorrhizal (AM) fungi can improve plant growth under salt stress. Kohler et al. (2006) demonstrated the beneficial effects of PGPR Pseudomonas mendocina strains on soil aggregate stabilization. Moreover, PGPR isolates such as Pseudomonas alcaligenes PsA15, Bacillus polymyxa BcP26, and Mycobacterium phlei MbP18 have been found to tolerate high temperatures and salt concentrations, offering them a competitive advantage in arid and saline soils like calcisol.

Studies by Kohler et al. (2009) investigated the impact of inoculation with Pseudomonas mendocina PGPR, alone or in combination with AM fungi, on the growth, nutrient uptake, and physiological activities of salt-stressed Lactuca sativa. Despite salt stress reducing lettuce growth, plants inoculated with *P. mendocina* showed significantly greater shoot biomass compared to controls, suggesting that selected PGPR inoculations could be an effective tool for mitigating salinity stress in salt-sensitive plants. The costs associated with mitigating soil salinity are considerable, impacting agriculture, biodiversity, and the environment. Understanding the osmotolerance mechanisms of PGPR strains such as Pseudomonas fluorescens MSP-393, including de novo synthesis of osmolytes and overproduction of salt-stress proteins, is crucial. Investigations into the interactions between PGPR and other microbes and their effects on crop plant physiology under varying soil salinity levels are in the early stages. Inoculations with selected PGPR and other microbes, particularly AM fungi, hold promise for alleviating salinity stress in salt-sensitive crops, offering potential strategies for sustainable agriculture in saline soils. Further extensive research is needed in this area to develop effective and environmentally friendly solutions.

Role of rhizospheric microbial interactions in environment and agriculture sustainability

Amid growing public concerns regarding the adverse effects of agrochemicals, there is a burgeoning interest in enhancing our understanding of microbial interactions within the rhizosphere and their potential benefits for agriculture and the environment. Beneficial microbial interactions in soil ecosystems play a pivotal role in regulating essential environmental processes, including the breakdown of complex organic matter into simpler forms of nitrogen and the modulation of plant growth and productivity. A conceptual framework illustrating the future contributions of Plant Growth-Promoting Rhizobacteria (PGPR), cyanobacteria, and rhizospheric microbial interactions to the advancement of sustainable agriculture and environmental practices has been outlined (Glick 1995; Bowen and Rovira 1999; Barea et al., 2002).

Numerous studies have underscored the intricate interactions between soil microbial communities, plant roots, and soil components at the root-soil interface. The dynamic environment known as the rhizosphere, shaped by the distinct physical, chemical, and biological characteristics compared to bulk soil, fosters increased microbial diversity and activity. Certain microbial interaction activities can be harnessed to develop biotechnological interventions, laying the groundwork for sustainable and environmentally friendly practices crucial for the stability and productivity of agricultural systems and natural ecosystems (Dashti et al., 1998).

PGPR and rhizobia, coexisting in the same microhabitats within the rhizosphere, engage in interactions during root colonization. In legumes, PGPR have been shown to enhance nodulation and nitrogen fixation. Field studies, particularly those employing 15N-based techniques, have provided evidence of the beneficial effects of microbial community interactions. PGPR-mediated enhancements in nodule formation suggest their involvement in producing plant hormones, highlighting the advantages of co-inoculation strategies. Certain Pseudomonas strains have demonstrated the ability to increase nodule numbers and reduce acetylene levels in soybean plants inoculated with B. japonicum. Previous research has suggested that plant growth-regulating substances produced by PGPR may influence nitrogen fixation and root nodulation. While the hypothesis that metabolites such as siderophores, phytoalexins, and flavonoids might enhance nodule formation warrants further investigation, some PGPRs have shown promise in facilitating the remediation of various contaminants from diverse sites.

Conclusion

Achieving an ideal agricultural system entails maintaining and enhancing human health, benefiting both producers and consumers economically and spiritually, safeguarding the environment, and meeting the increasing food demands of a growing global population. In the face of indiscriminate population growth, land degradation, and rising food requirements, the sustainable management of soil quality emerges as a pivotal aspect for ensuring food security and poverty alleviation, particularly in developing nations.

The prohibitive cost of chemical nitrogen fertilizers coupled with the limited purchasing power of many farmers hampers their optimal utilization, thereby impeding crop production. Additionally, significant amounts of urea nitrogen are lost through various mechanisms such as ammonia volatilization, denitrification, and leaching, leading to environmental pollution issues. The adoption of biological nitrogen fixation technology holds promise in reducing reliance on urea nitrogen, preserving soil organic matter, and mitigating environmental pollution to a considerable extent. Various biofertilizer systems incorporating Plant Growth-Promoting Rhizobacteria (PGPR) and cyanobacteria are currently utilized on a small scale, particularly in rice agroecosystems. However, before widespread adoption of microbial biofertilizers at the farm level, further research is necessary to assess their nitrogen-supplementing potentials. Noteworthy advancements have been made globally in bacterial and cyanobacterial biofertilizer technology, demonstrating its efficacy in enhancing soil fertility and boosting rice agriculture yields. Nevertheless, ongoing refinement is essential for maximizing the benefits of this technology within sustainable agriculture development initiatives.

PGPR and cyanobacteria serve as valuable model systems, offering novel genetic resources and bioactive compounds with versatile applications in agriculture and environmental sustainability. Advancements in understanding the diversity, colonization mechanisms, and interactions of PGPR and cyanobacteria, as well as in formulation and application techniques, hold promise for their integration into sustainable agricultural management practices.

The environmentally sustainable approach provided by PGPR and cyanobacteria holds potential for enhancing crop production and health. Leveraging molecular techniques enhances our capacity to comprehend and manage rhizosphere ecosystems, potentially leading to the development of improved products. Genetic enhancement of PGPR strains to enhance colonization and effectiveness, as well as the manipulation of host crops to promote beneficial microorganism proliferation, are avenues being explored. Additionally, rigorous health and safety testing is imperative to address concerns such as non-target effects, toxigenicity, allergenicity, pathogenicity, environmental persistence, and the potential for horizontal gene transfer.

Reference:

Abd-Alla M.H. (1994). Solubilization of rock phosphates by *Rhizobium* and *Bradyrhizobium. Folia Microbiol* 39: 53-56.

Abdalla M.H., Omer S.A. (2001). Survival of Rhizobia/Bradirhizobia and a rock phosphate solubilizing fungus *Aspergillus niger* on various carriers from some agro industrial wastes and their effect on nodulation and growth of faba bean and soybean. *J Plant Nutrition* 24: 161-172.

Acea M.J., Fernandez A.P., DizCid N. (2003). Cyanobacterial inoculation of heated soils: effect on microorganisms of C and N cycles and on chemical composition in soil surface. *Soil Biol. Biochemistry* 35: 513–524.

Alagawadi, A.R., Gaur, A.C. (1992). Inoculation of *Azospirillum brasilense* and phosphate-solubilizing bacteria on yield of sorghum (*Sorghum bicolor* L. Moench) in dry land. *Trop. Agric* 69:347–350.

Baliah, N. T., Pandiarajan, G., & Kumar, B. M. (2016). Isolation, identification and characterization of phosphate solubilizing bacteria from different crop soils of Srivilliputtur Taluk, Virudhunagar District, Tamil Nadu. *Tropical Ecology*, *57*(3), 465-474.

Barea J.M., Azcon R., Azcon Aguilar C., (2004). Mycorrhizal fungi and plant growth promoting rhizobacteria. In: Varma, A., Abbott, L., Werner, D., Hampp, R. (Eds.),

Belimov, A.A., Hontzeas, N., Safronova, V.I., Demchinskaya, S.V., Piluzza, G., Bullitta, S., Glick, B.R., (2005). Cadmium tolerant plant growth-promoting bacteria associated with the roots of Indian mustard *(Brassica juncea L. Czern.) Soil Biol. Biochem* 12:130-132

Bisen, K., Keswani, C., Mishra, S., Saxena, A., Rakshit, A., Singh, H.B. (2015) Unrealized Potential of Seed Biopriming for Versatile Agriculture. In: Nutrient Use Efficiency: from Basics to Advances. Eds. A, Rakshit, H.B. Singh, A. Sen. Springer India, pp. 193-206.

Bowen, G.D., Rovira, A.D., (1999). The rhizosphere and its management to improve plant growth. *Advan Agron* 66: 1-10.

Brisson N, Gate P, Gouache D, Charmet G, Oury FX, Huard F (2010). Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crop Res* 119:201–12.

Chabot R., Anton H., Cescas M.P. (1996). Growth promotion of maize and lettuce by phosphate solubilizing *Rhizobium leguminosarum* bio var *phaseoli*. *Plant Soil* 184: 311-321.

Dashti, N., Zhang, F., Hynes, R., & Smith, D. L. (1998). Plant growth promoting rhizobacteria accelerate nodulation and increase nitrogen fixation activity by field grown soybean [Glycine max (L.) Merr.] under short season conditions. *Plant and Soil*, *200*, 205-213.

Dhankhar, R., Sheoran, S., Dhaka, A., & Soni, R. (2013). The role of phosphorus solublizing bacteria (PSB) in soil management-an overview. *International Journal of Development Research*, *3*(9), 31-36.

Earanna N., Govindan R. (2002). Role of biofertilizers in mulberry production- a review. Indian J. Seric 41: 92–99.

Filippi MCC, da Silva GB, Silva-Lobo VL, Côrtes MVCB, Moraes AJG, Prabhu AS. (2011). Leaf blast *(Magnaporthe oryzae)* suppression and growth promotion by rhizobacteria on aerobic rice in Brazil. *Biol Control* 23: 246-252.

Flaibani A., Olsen Y., Painter T.J. (1989). Polysaccharides in desert reclamation: composition of exocellular proteoglycan complexes produced by filamentous blue-green and unicellular green edaphic algae. *Carbohydrate Research* 190: 235-248.

Fraceto L.F., Maruyama, C.R., Guilger, M., Mishra, S., Keswani, C., Singh, H.B., deLima, R., (2018) *Trichoderma harzianum* based novel formulations: Potential Applications for Management of Next-Gen agricultural challenges. Journal of Chemical Technology and Biotechnology 93: 2056–2063. DOI: 10.1002/jctb.5613

Galal Y.G.M., (2003). Assessment of nitrogen availability to wheat *(Triticum aestivum L.)* from inorganic and organic N sources as affected by *Azospirillum brasilense* and *Rhizobium leguminosarum* inoculation. *Egyptian J. Microbiol* 38: 57-73.

Glick B.R., Patten C.L., Holguin G., Penrose D.M. (1999). Biochemical and Genetic Mechanisms Used by Plant Growth Promoting Bacteria. *Soil Microbiol* 29: 1233-1239.

Halder A.K., Chakrabarty P.K. (1993). Solubilization of inorganic phosphate by *Rhizobium*., *Folia Microbial* 38, 325-330.

Han H., Supanjani S.K., Lee D., (2004). Effect of co-inoculation with phosphate and potassium solubilizing bacteria on mineral uptake and growth of pepper and cucumber. *Agron sci* 24: 234-240

Kavino M., Harish S., Kumar N., Saravanakumar D., Samiyappan R. (2010). Effect of chitinolytic PGPR on growth, yield and physiological attributes of banana (*Musa* spp.) under field conditions. *Appl. Soil Eco.* 45: 71-77.

Kavino M., Harish S., Kumar N., Saravanakumar D., Samiyappan R. (2010). Effect of chitinolytic PGPR on growth, yield and physiological attributes of banana (*Musa* spp.) under field conditions. *Appl. Soil Eco.* 45: 71-77.

Keswani C., (2015a). Ecofriendly Management of Plant Diseases by Biosynthesised Secondary Metabolites of *Trichoderma* spp. Journal of Brief Ideas 10.5281/zenodo.15571

Keswani C., (2015a). Ecofriendly Management of Plant Diseases by Biosynthesised Secondary Metabolites of *Trichoderma* spp. Journal of Brief Ideas 10.5281/zenodo.15571

Keswani, C., (2015b). Proteomic studies of thermotolerant strains of *Trichoderma* spp. Ph.D. thesis. Banaras Hindu University, Varanasi, India. P. 126

Keswani, C., Bisen, K., Singh, V., Sarma, B.K., and Singh H.B. (2016) Formulation Technology of Biocontrol Agents: Present Status and Future Prospects. In: Bioformulations: for Sustainable Agriculture. Eds. N.K. Arora. Springer India, pp. 35-52.

Keswani, C., Mishra, S., Sarma, B.K., Singh, S.P. and H.B. Singh. (2014). Unravelling the efficient applications of secondary metabolites of various *Trichoderma* spp. Applied Microbiology and Biotechnology 98: 533–544.

Kleiner, E. F., & Harper, K. T. (1977). Soil properties in relation to cryptogamic groundcover in Canyonlands National Park. *Rangeland Ecology & Management/Journal of Range Management Archives*, *30*(3), 202-205.

Kohler J., Caravaca F., Carrasco L., Roldan A. (2006). Contribution of *Pseudomonas mendocina* and *Glomus intraradices* to aggregates stabilization and promotion of biological properties in rhizosphere soil of lettuce plants under field conditions. *Soil Use Manage* 22: 298-304.

Krey T, Vassilev N, Baum C, Eichler-Löbermann (2013). Effects of long-term phosphorus application and plant-growth promoting rhizobacteria on maize phosphorus nutrition under field conditions. *Eur J Soil Biol* 65: 245–252.

Lobell D.B., Schlenker W., Costa-Roberts J. (1999). Climate trends and global crop production. *Sin Science*, 70: 243-249.

M. Hagemann, M. Henneberg, V. Felde, S. L. Drahorad, S. M. Berkowicz, P. Felix-Henningsen, et al., “Cyanobacterial diversity in biological soil crusts along a precipitation gradient, Northwest Negev Desert,” Isr. Microb. Ecol. 70, 219–230 (2015).

M. Hagemann, M. Henneberg, V. Felde, S. L. Drahorad, S. M. Berkowicz, P. Felix-Henningsen, et al., “Cyanobacterial diversity in biological soil crusts along a precipitation gradient, Northwest Negev Desert,” Isr. Microb. Ecol. 70, 219–230 (2015).

M. Ramirez, M. Hernandez-Marine, P. Mateo, E. Berrendero, and M. Roldan, “Polyphasic approach and adaptative strategies of Nostoc cf. commune (Nostocales, Nostocaceae) growing on Mayan monuments,” Fottea 1, 73–86 (2011).

M. Ramirez, M. Hernandez-Marine, P. Mateo, E. Berrendero, and M. Roldan, “Polyphasic approach and adaptative strategies of Nostoc cf. commune (Nostocales, Nostocaceae) growing on Mayan monuments,” Fottea 1, 73–86 (2011).

Nisha R., Kaushik A., Kaushik C.P. (2007). Effect of indigenous cyanobacterial application on structural stability and productivity of an organically poor semi-arid soil. *Geoderma* 138: 49-56.

Orlovsky L., Dourikov M., Babaev A., (2004). Temporal dynamics and productivity of biogenic soil crusts in the central Karakum desert, Turkmenistan. *J. Arid Environ* 25: 325-336.

Plant Surface Microbiology. Springer-Verlag, Heidelberg, Germany, pp. 351

Ram, R.M., Keswani, C., Bisen, K., Tripathi, R., Singh, S.P., Singh, H.B. (2018). Biocontrol Technology: Eco-Friendly Approaches for Sustainable Agriculture. In: Brah, D., Azevedo, V. (eds) Omics Technologies and Bio-Engineering: Towards Improving Quality of Life Volume II Microbial, Plant, Environmental and Industrial Technologies. Academic Press, London, U.K. pp. 177-190.

Ramazan C., Akmakc I., Figen A., Adil A., Fikrettin S., Ahin B.C., (2005). Growth promotion of plants by plant growth-promoting rhizobacteria under greenhouse and two different field soil conditions. *Biochemistry* 38: 1482-1487.

Rodriguez H., Fraga R., (1999). Phosphate solubilizing bacteria and their role in plant growth promotion. *Biotech. Advanced*, 17: 319-339.

Sheng X.F., He L.Y. (2006). Solubilization of potassium bearing minerals by a wild type strain of *Bacillus edaphicus* and its mutants and increased potassium uptake by wheat. *Can. J. Microbiol.* 102: 1283-1292.

Singh G.R., Pandya K.S., Choudhary K.K., Sharma R.B. (1997). Biofertilizers in crop production. *Indian Farm* 139: 74-79.

Singh, H.B, Keswani, C., Reddy, M.S., Royano, E.S., García-Estrada, C. (Eds.). Secondary Metabolites of Plant Growth Promoting Rhizomicroorganisms: Discovery and Applications (2019) Springer-Nature, Singapore. 392 pages, ISBN- 978-981-13-5861-6.

Singh, H.B, Sarma, B.K., Keswani, C. (Eds.). Agriculturally Important Microorganisms: Commercialization and Regulatory Requirements in Asia. (2016b). Springer, Singapore. 336 pages, ISBN-13: 978-9811025754

Singh, H.B., Jain, A, Saxena, A., Singh, A., Keswani, C., Sarma, B.K. and S. Mishra. (2014). Deciphering the pathogenic behaviour of phytopathogens using molecular tools In: Biological Controls for Preventing Food Deterioration: Strategies for Pre-and Postharvest Management. Ed. Neeta Sharma. John Wiley & Sons, Ltd., Chichester, UK, pp. 377-408.

Singh, H.B., Keswani, C., Kartikay Bisen, Sarma, B.K., Chakrabarty, P.K. (2016a) Development and Application of Agriculturally Important Microorganisms in India. In: Agriculturally

Important Microorganisms: Commercial and regulatory requirement in Asia. Eds. H. B. Singh, B. K. Sarma, C. Keswani. Springer Singapore, pp.167-181.

Tajini F., Trabelsi M., Drevon J.J. (2013). Combined inoculation with *Glomus intraradices* and *Rhizobium tropici* CIAT899 increases phosphorus use efficiency for symbiotic nitrogen fixation in common bean *(phaseolus vulgaris L.). Saudi J Biol Sci* 137: 57-69.

Tanwar S.P.S., Sharma G.L., Chahar M.S. (2002). Effect of phosphorus and biefertilizers on the growth and productivity of black gram. *Annl. Agric. Res.* 23: 491-493.

Yasmin S., Bakar M.A.R., Malik K.A., Hafeez F.Y. (2004). Isolation, characterization and beneficial effects of rice associated plant growth promoting bacteria from Zanzibar soils. *J Basic Microbiology* 38: 775-782.

Zahir A., Arshad Z.M., Frankenberger W.F. (2004). Plant growth promoting rhizobacteria. *Adv. Agron* 81: 97-168.