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A Review of Biofertilizers : An Ecofriendly Technology for Soil Health Management in Sustainable Agriculture

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ABSTRACT: A biofertilizer is a substance which contains living micro-organisms which, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant.[1] Biofertilizers add nutrients through the natural processes of nitrogen fixation, solubilizing phosphorus, and stimulating plant growth through the synthesis of growth-promoting substances. The micro-organisms in biofertilizers restore the soil's natural nutrient cycle and build soil organic matter. Through the use of biofertilizers, healthy plants can be grown, while enhancing the sustainability and the health of the soil. Biofertilizers can be expected to reduce the use of synthetic fertilizers and pesticides, but they are not yet able to replace their use. Since they play several roles, a preferred scientific term for such beneficial bacteria is "plant-growth promoting rhizobacteria" (PGPR).

KEYWORDS: biofertilizers, eco-friendly, soil health management, agriculture, technology, beneficial microbes, PGPR

I. INTRODUCTION

Biofertilizers provide "eco-friendly" organic agro-input. Biofertilizers such as *Rhizobium*, *Azotobacter*, *Azospirilium* and blue green algae(BGA) have been in use a long time. *Rhizobium* inoculant is used for leguminous crops. *Azotobacter* can be used with crops like wheat, maize, mustard, cotton, potato and other vegetable crops. *Azospirillum* inoculations are recommended mainly for sorghum, millets, maize, sugarcane and wheat. Blue green algae belonging to the general cyanobacteria genera, *Nostoc*, *Anabaena*, *Tolypothrix* and *Aulosira*, fix atmospheric nitrogen and are used as inoculations for paddy crop grown both under upland and low-land conditions. *Anabaena* in association with water fern *Azolla* contributes nitrogen up to 60 kg/ha/season and also enriches soils with organic matter.[2][3] Seaweeds are rich in various types of mineral elements (potassium, phosphorus, trace elements etc) hence they are extensively used as manure by people of coastal districts. Seaweed - manure also helps in breaking down clays. Fucus is used by Irish people as manure on a large scale. In tropical countries bottom mud of dried up ponds which contain abundant blue green algae is regularly used as manure in fields. The mixture of seaweeds and blue green algae may serve as ideal fertilizer.

Phosphate-solubilizing bacteria

Other types of bacteria, so-called phosphate-solubilizing bacteria, such as *Pantoea agglomerans* strain P5 or *Pseudomonas putida* strain P13,[4] are able to solubilize the insoluble phosphate from organic and inorganic phosphate sources.[5] In fact, due to immobilization of phosphate by mineral ions such as Fe, Al and Ca or organic acids, the rate of available phosphate (P_i) in soil is well below plant needs. In addition, chemical P_i fertilizers are also immobilized in the soil, immediately, so that less than 20 percent of added fertilizer is absorbed by plants. Therefore, reduction in P_i resources, on one hand, and environmental pollutions resulting from both production and applications of chemical P_i fertilizer, on the other hand, have already demanded the use of phosphate-solubilizing bacteria or phosphate biofertilizers.

Benefits

1. Biofertilizers are means of fixing the nutrient availability in the soil. Generally Nitrogen deficiencies.
2. Since a bio-fertilizer is technically living, it can symbiotically associate with plant roots. Involved microorganisms could readily and safely convert complex organic material into simple compounds, so that

they are easily taken up by the plants. Microorganism function is in long duration, causing improvement of the soil fertility. It maintains the natural habitat of the soil. It increases crop yield by 20-30%, replaces chemical nitrogen and phosphorus by 30%, and stimulates plant growth. It can also provide protection against drought and some soil-borne diseases.

3. It has also been shown that to produce a larger quantity of crops, biofertilizers with the ability of nitrogen fixation and phosphorus solubilizing would lead to the greatest possible effect.[6]
4. They advance shoot and root growth of many crops versus control groups.[7] This can be important when implementing new seed growth.
5. Biofertilizers also promote healthy soil, leading to greater farming sustainability.

Groups of biofertilizers

1. *Azolla-Anabena* symbiosis: Azolla is a small, eukaryotic, aquatic fern having global distribution. Prokaryotic blue green algae Anabena azolla resides in its leaves as a symbiont. Azolla is an alternative nitrogen source. This association has gained wide interest because of its potential use as an alternative to chemical fertilizers.
2. *Rhizobium*: Symbiotic nitrogen fixation by *Rhizobium* with legumes contribute substantially to total nitrogen fixation. *Rhizobium* inoculation is a well-known agronomic practice to ensure adequate nitrogen.[8][9]
3. *Streptomyces grisoflavus*[10]
4. Unigrow (UniGrow): a commercial bio fertilizer that is currently in use. It is made with a by-product of palm oil production and it contains a microbial element[11] It has been shown to have promising results in studies.[12]

Areas in need of improvement

Biofertilizers have been shown to have varying effects in different environments,[13] and even within the same environment. This is something that many scientists have been working on, however there is no perfect solution at this time. They however, have been shown to have the most profound effects in drier climates.[6] In the future, it is hoped that biofertilizers effects will be better controlled and regulated in all environments.

II. DISCUSSION

Microbial inoculants also known as soil inoculants or bioinoculants are agricultural amendments that use beneficial rhizosphericic or endophytic microbes to promote plant health. Many of the microbes involved form symbiotic relationships with the target crops where both parties benefit (mutualism). While microbial inoculants are applied to improve plant nutrition, they can also be used to promote plant growth by stimulating plant hormone production.[1][2] Although bacterial and fungal inoculants are common, inoculation with archaea to promote plant growth is being increasingly studied. [3]

Research into the benefits of inoculants in agriculture extends beyond their capacity as biofertilizers. Microbial inoculants can induce systemic acquired resistance (SAR) of crop species to several common crop diseases (provides resistance against pathogens). So far SAR has been demonstrated for powdery mildew (*Blumeria graminis* f. sp. *hordei*, Heitefuss, 2001), take-all (*Gaeumannomyces graminis* var. *tritici*, Khaosaad *et al.*, 2007), leaf spot (*Pseudomonas syringae*, Ramos Solano *et al.*, 2008) and root rot (*Fusarium culmorum*, Waller *et al.* 2005).

However, it is increasingly recognized that microbial inoculants often modify the soil microbial community (Mawarda *et al.*, 2020).

Bacterial

Rhizobacterial inoculants

The rhizobacteria commonly applied as inoculants include nitrogen-fixers, phosphate-solubilisers and other root-associated beneficial bacteria which enhance the availability of the macronutrients nitrogen and phosphorus to the host plant. Such bacteria are commonly referred to as plant growth promoting rhizobacteria (PGPR).

Nitrogen-fixing bacteria

The most commonly applied rhizobacteria are *Rhizobium* and closely related genera. *Rhizobium* are nitrogen-fixing bacteria that form symbiotic associations within nodules on the roots of legumes. This increases host nitrogen nutrition and is important to the cultivation of soybeans, chickpeas and many other leguminous crops. For nonleguminous crops, *Azospirillum* has been demonstrated to be beneficial in some cases for nitrogen fixation and plant nutrition.[1]

For cereal crops, diazotrophic rhizobacteria have increased plant growth,[4] grain yield (Caballero-Mellado *et al.*, 1992), nitrogen and phosphorus uptake,[4] and nitrogen (Caballero-Mellado *et al.*, 1992), phosphorus (Caballero-Mellado *et al.*, 1992; Belimov *et al.*, 1995) and potassium content (Caballero-Mellado *et al.*, 1992). Rhizobacteria live in root nodes, and are associated with legumes.

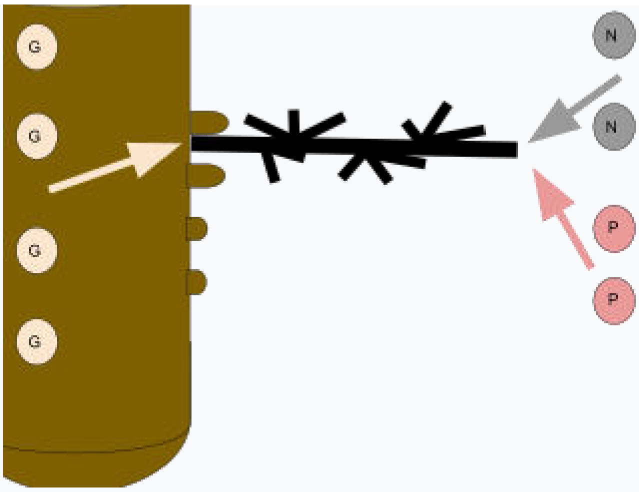
Phosphate-solubilising bacteria

To improve phosphorus nutrition, the use of phosphate-solubilising bacteria (PSB) such as *Agrobacterium radiobacter* has also received attention (Belimov *et al.*, 1995a; 1995b; Singh & Kapoor, 1999). As the name suggests, PSB are free-living bacteria that break down inorganic soil phosphates to simpler forms that enable uptake by plants.

Fungal inoculants

Symbiotic relationships between fungi and plant roots is referred to as a Mycorrhiza association.[5] This symbiotic relationships is present in nearly all land plants and give both the plant and fungi advantages to survival.[5] The plant can give upwards of 5-30% of its energy production to the fungi in exchange for increasing the root absorptive area with hyphae which gives the plant access to nutrients it would otherwise not be able to attain.[5][6] The two most common mycorrhizae are arbuscular mycorrhizae and ectomycorrhizae. Ectomycorrhizae associations are most commonly found in woody-species, and have less implications for agricultural systems.[7]

Arbuscular mycorrhiza



This diagram shows the beneficial symbiotic relationship between a plants roots and a fungus partner, which is referred to as a mycorrhiza association.[5] Plants can give upwards of 5-30% of their photosynthetic production to this relationship, represented by G, in exchange for enhanced nutrient uptake, via hyphae, which extend the plants root absorptive area, giving it access to nutrients it would otherwise not be able to attain, which is represented by N and P.[5]

Arbuscular mycorrhiza (AM) has received attention as a potential agriculture amendment for its ability to access and provide the host plant phosphorus.[7] Under a reduced fertilization greenhouse system that was inoculated with a mixture of AM fungi and rhizobacteria, tomato yields that were given from 100% fertility were attained at 70% fertility.[8] This 30% reduction in fertilizer application can aid in the reduction of nutrient pollution, and help prolong finite mineral resources such as phosphorus (Peak phosphorus). Other effects include increases in salinity tolerance,[9] drought tolerance,[10] and resistance to trace metal toxicity.[11]

Fungal partners

Fungal inoculation alone can benefit host plants. Inoculation paired with other amendments can further improve conditions. Arbuscular mycorrhizal inoculation combined with compost is a common household amendment for personal gardens, agriculture, and nurseries. It has been observed that this pairing can also promote microbial functions in soils that have been affected by mining.[12]

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| Volume 6, Issue 7, July 2023 |

Certain fungal partners do best in specific ecotones or with certain crops. Arbuscular mycorrhizal inoculation paired with plant growth promoting bacteria resulted in a higher yield and quicker maturation in upland rice paddys.[13]

Maize growth improved after an amendment of arbuscular mycorrhizae and biochar. This amendment can also decrease cadmium uptake by crops.[14]

Inoculant usage

Fungal inoculants can be used with or without additional amendments in private gardens, homesteads, agricultural production, native nurseries, and land restoration projects.

Composite inoculants

The combination of strains of Plant Growth Promoting Rhizobacteria (PGPR) has been shown to benefit rice and barley.[15][16] The main benefit from dual inoculation is increased plant nutrient uptake from both soil and fertilizer.[15] Multiple strains of inoculant have also been demonstrated to increase total nitrogenase activity compared to single strains of inoculants, even when only one strain is diazotrophic.[15][17][18]

PGPR and arbuscular mycorrhizae in combination can be useful in increasing wheat growth in nutrient poor soil[19] and improving nitrogen-extraction from fertilised soils.[20]

III. RESULTS

Rhizobacteria are root-associated bacteria that can have a detrimental (parasitic varieties), neutral or beneficial effect on plant growth. The name comes from the Greek *rhiza*, meaning root. The term usually refers to bacteria that form symbiotic relationships with many plants (mutualism). Rhizobacteria are often referred to as plant growth-promoting rhizobacteria, or PGPRs. The term PGPRs was first used by Joseph W. Kloepper in the late 1970s and has become commonly used in scientific literature.[1]

Generally, about 2–5% of rhizosphere bacteria are PGPR.[2] They are an important group of microorganisms used in biofertilizer. Biofertilization accounts for about 65% of the nitrogen supply to crops worldwide. PGPRs have different relationships with different species of host plants. The two major classes of relationships are rhizospheric and endophytic. Rhizospheric relationships consist of the PGPRs that colonize the surface of the root, or superficial intercellular spaces of the host plant, often forming root nodules. The dominant species found in the rhizosphere is a microbe from the genus *Azospirillum*.[3][Endophytic relationships involve the PGPRs residing and growing within the host plant in the apoplastic space.[1]

Nitrogen fixation is one of the most beneficial processes performed by rhizobacteria. Nitrogen is a vital nutrient to plants and gaseous nitrogen (N_2) is not available to them due to the high energy required to break the triple bonds between the two atoms.[4] Rhizobacteria, through nitrogen fixation, are able to convert gaseous nitrogen (N_2) to ammonia (NH_3) making it an available nutrient to the host plant which can support and enhance plant growth. The host plant provides the bacteria with amino acids so they do not need to assimilate ammonia.[5] The amino acids are then shuttled back to the plant with newly fixed nitrogen. Nitrogenase is an enzyme involved in nitrogen fixation and requires anaerobic conditions. Membranes within root nodules are able to provide these conditions. The rhizobacteria require oxygen to metabolize, so oxygen is provided by a hemoglobin protein called leghemoglobin which is produced within the nodules.[4] Legumes are well-known nitrogen-fixing crops and have been used for centuries in crop rotation to maintain the health of the soil.

Symbiotic relationships

The symbiotic relationship between rhizobacteria and their host plants is not without costs. For the plant to be able to benefit from the added available nutrients provided by the rhizobacteria, it needs to provide a place and the proper conditions for the rhizobacteria to live. Creating and maintaining root nodules for rhizobacteria can cost between 12–25% of the plant's total photosynthetic output. Legumes are often able to colonize early successional environments due to the unavailability of nutrients. Once colonized, though, the rhizobacteria make the soil surrounding the plant more nutrient rich, which in turn can lead to competition with other plants. The symbiotic relationship, in short, can lead to increased competition.[4]

PGPRs increase the availability of nutrients through the solubilization of unavailable forms of nutrients and by the production of siderophores which aids in the facilitating of nutrient transport. Phosphorus, a limiting nutrient for plant growth, can be plentiful in soil, but is most commonly found in insoluble forms. Organic acids and phosphotases

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released by rhizobacteria found in plant rhizospheres facilitate the conversion of insoluble forms of phosphorus to plant-available forms such as $H_2PO_4^-$. PGPR bacteria include *Pseudomonas putida*, *Azospirillum fluorescens*, and *Azospirillum lipoferum* and notable nitrogen-fixing bacteria associated with legumes includes *Allorhizobium*, *Azorhizobium*, *Bradyrhizobium*, and *Rhizobium*.[5]

Though microbial inoculants can be beneficial for crops, they are not widely used in industrial agriculture, as large-scale application techniques have yet to become economically viable. A notable exception is the use of rhizobial inoculants for legumes such as peas. Inoculation with PGPRs ensures efficient nitrogen fixation, and they have been employed in North American agriculture for over 100 years.

Plant growth-promoting rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) were first defined by Kloepper and Schroth[6] to be soil bacteria that colonize the roots of plants following inoculation onto seed and that enhance plant growth.[7] The following are implicit in the colonization process: ability to survive inoculation onto seed, to multiply in the spermosphere (region surrounding the seed) in response to seed exudates, to attach to the root surface, and to colonize the developing root system.[8] The ineffectiveness of PGPR in the field has often been attributed to their inability to colonize plant roots.[3][9] A variety of bacterial traits and specific genes contribute to this process, but only a few have been identified. These include motility, chemotaxis to seed and root exudates, production of pili or fimbriae, production of specific cell surface components, ability to use specific components of root exudates, protein secretion, and quorum sensing. The generation of mutants altered in expression of these traits is aiding our understanding of the precise role each one plays in the colonization process.[10][11]

Progress in the identification of new, previously uncharacterized genes is being made using nonbiased screening strategies that rely on gene fusion technologies. These strategies employ reporter transposons[12] and in vitro expression technology (IVET)[13] to detect genes expressed during colonization.

Using molecular markers such as green fluorescent protein or fluorescent antibodies, it is possible to monitor the location of individual rhizobacteria on the root using confocal laser scanning microscopy.[3][14][15] This approach has also been combined with an rRNA-targeting probe to monitor the metabolic activity of a rhizobacterial strain in the rhizosphere and showed that bacteria located at the root tip were most active.[16]

Mechanisms of action

PGPRs enhance plant growth by direct and indirect means, but the specific mechanisms involved have not all been well characterized.[8] Direct mechanisms of plant growth promotion by PGPRs can be demonstrated in the absence of plant pathogens or other rhizosphere microorganisms, while indirect mechanisms involve the ability of PGPRs to reduce the harmful effects of plant pathogens on crop yield. PGPRs have been reported to directly enhance plant growth by a variety of mechanisms: fixation of atmospheric nitrogen transferred to the plant,[17] production of siderophores that chelate iron and make it available to the plant root, solubilization of minerals such as phosphorus, and synthesis of phytohormones.[18] Direct enhancement of mineral uptake due to increases in specific ion fluxes at the root surface in the presence of PGPRs has also been reported. PGPR strains may use one or more of these mechanisms in the rhizosphere. Molecular approaches using microbial and plant mutants altered in their ability to synthesize or respond to specific phytohormones have increased understanding of the role of phytohormone synthesis as a direct mechanism of plant growth enhancement by PGPRs.[19] PGPR that synthesize auxins, gibberellins and kinetins or that interfere with plant ethylene synthesis have been identified.[20]

Development of PGPRs into biofertilisers and biopesticides could be a novel way of increasing crop yield and decreasing disease incidence, [21] whilst decreasing dependency on chemical pesticides and fertilisers which can often have harmful effects on the local ecology and environment.[22]

Pathogenic roles

Studies conducted on sugar beet crops found that some root-colonizing bacteria were deleterious rhizobacteria (DRB). Sugar beet seeds inoculated with DRB had reduced germination rates, root lesions, reduced root elongation, root distortions, increased fungi infection, and decreased plant growth. In one trial the sugar beet yield was reduced by 48%.[23]

Six strains of rhizobacteria have been identified as being DRB. The strains are in the genera *Enterobacter*, *Klebsiella*, *Citrobacter*, *Flavobacterium*, *Achromobacter*, and *Arthrobacter*. Due to a large number of taxonomic species yet to be described, complete characterization has not been possible as DRB are highly variable.[23]

The presence of PGPRs has proven to reduce and inhibit the colonization of DRB on sugar beet roots. Plots inoculated with PGPRs and DRBs had an increase in production of 39% while plots only treated with DRBs had a reduction in production of 30%.[23]

Biocontrol

Rhizobacteria are also able to control plant diseases that are caused by other bacteria and fungi. Disease is suppressed through induced systemic resistance and through the production of antifungal metabolites. *Pseudomonas* biocontrol strains have been genetically modified to improve plant growth and improve the disease resistance of agricultural crops. In agriculture, inoculant bacteria are often applied to the seed coat of seeds prior to being sown. Inoculated seeds are more likely to establish large enough rhizobacterial populations within the rhizosphere to produce notable beneficial effects on the crop.[1]

They can also combat pathogenic microbes in cattle. Different forage species regulate their own rhizosphere to varying degrees and favouring various microbes. Kyselková et al 2015 find planting forage species known to encourage native rhizobacteria retards the spread within the soil of antibiotic resistance genes of cow faeces bacteria.[24][25]

IV. CONCLUSIONS

Seaweed fertiliser (or fertilizer) is organic fertilizer made from seaweed that is used in agriculture to increase soil fertility and plant growth. The use of seaweed fertilizer dates back to antiquity and has a broad array of benefits for soils. Seaweed fertilizer can be applied in a number of different forms, including refined liquid extracts and dried, pulverized organic material.[1][2] Through its composition of various bioactive molecules, seaweed functions as a strong soil conditioner, bio-remediator, and biological pest control, with each seaweed phylum offering various benefits to soil and crop health.[1] These benefits can include increased tolerance to abiotic stressors, improved soil texture and water retention, and reduced occurrence of diseases.[1][3]

On a broader socio-ecological scale, seaweed aquaculture and fertilizer development have significant roles in biogeochemical nutrient cycling through carbon storage and the uptake of nitrogen and phosphorus.[4][5] Seaweed fertilizer application to soils can also alter the structure and function of microbial communities. Seaweed aquaculture has the potential to yield ecosystem services by providing a source of nutrition to human communities and a mechanism for improving water quality in natural systems and aquaculture operations.[6][7][8] The rising popularity of organic farming practices is drawing increased attention towards the various applications of seaweed-derived fertilizers and soil additives. While the seaweed fertilizer industry is still in its infancy, it holds significant potential for sustainable economic development as well as the reduction of nutrient runoff in coastal systems.[9] There are however ongoing challenges associated with the use and production of seaweed fertilizer including the spread of diseases and invasive species, the risk of heavy metal accumulation, and the efficiency and refinement of production methods.[10][11][12][13]

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