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Plant Growth Promoting Fungi (PGPF) for Ecologically Sound Agriculture and its Market Trend Evolution

MUM TATUNG[1], ANU SENG CHAUPOO[2] and CHITTA RANJAN DEB[1*]

[1]Department of Botany, Nagaland University, Lumami, Nagaland, India.
[2]Department of Horticulture, School of Agricultural Science, Nagaland University, Medzhiphema, Nagaland, India.

Abstract
Amidst the escalating concerns regarding the detrimental impact of harmful agrochemicals, the development of organic fertilizers has assumed paramount importance in curbing reliance on syntheticcounterparts within agricultural practices. Plant growth promoting fungi (PGPF) has emerged as a promising solution, owing to its capacity to enhance plant development via many pathways, including siderophore synthesis, phosphate solubilizationand indole-3-acetic acid (IAA) production, alongside other beneficial traits such as stress tolerance and biocontrol activity. The increasing awareness of the adverse consequences of harsh agrochemicals has prompted a shift towards organic biofertilizers, aligning with the principles of sustainable agriculture. Numerous countries have already begun implementing stringent regulations on use of harmful chemicals while actively promoting the adoption of microbe-based products to enhance plant growth. While it's not feasible to completely eliminate synthetic agrochemicals overnight, the incorporation of biofertilizers can substantially reduce their usage. The principal goal of this comprehensive review is to delve into the pivotal role of PGPF in fostering environmentally responsible agriculture. Additionally, it digs into the emerging market trends linked with products based on PGPF.

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Introduction

There is a growing demand for food to fulfill the requirement of the world with ever increasing human population has driven farmers to significantly escalate crop production. Consequently, there has been a widespread adoption of synthetic fertilizers, pesticides, and herbicides in large quantities.[1-4] However, the continuous use of these chemicals has led to decline in soil quality and lead to various detrimental consequences, including groundwater contamination, reduced microbial diversity, reduced crop yield and quality, development of susceptibility

CONTACT Chitta Ranjan Deb debchitta@rediffmail.com Department of Botany, Nagaland University, Lumami, Nagaland, India.

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to pathogens etc. The excessive use of chemical fertilizers became prominent during the Green Revolution, spanning from1940s to the 1970s in Mexico, and subsequently extended to numerous other developing countries.[1,3] Though, it significantly boosted the crop production, but it also brought forth negative implications with enduring impacts on various facets of human society, such as soil and water pollution and several health hazards stemming from the harmful chemicals present in these agrochemicals.[5] To mitigate these concerns, sustainable framing practices that aim to reduce the use of chemical fertilizers have gained popularity. This paradigm shift is driven by the belief that organic crops are healthier and have a lower environmental impact compared to conventionally grown crops. Plant growth promoting fungi (PGPF) are beneficial fungi (mycorrhizal, rhizospheric, endophytic) contribute to growth and development of plants. Their ability to enhance plant growth makes them suitable for organic based agriculture and presents a new innovative approach with reduced reliance on traditional inorganic fertilizers.[1,6] The PGPF extends to the root system of the plants, aiding in nutrient and water uptake and improving the physical properties of the soil by modifying its structure. For example, fungal hyphae can create macro-aggregate by entangling soil particles with each other.[2] Among the well-studied root associated fungi are Arbuscular Mycorrhizal Fungi (AMF), which forms symbiotic relationship with approximately 80% of the land plants species including agricultural crops. The AMF provides numerous benefits to the plants including enhanced uptake of mineral nutrients and water in exchange of carbon source from plants.[7] The association between PGPF and plant roots has been demonstrated to influence plant growth, enhance mineral nutrient absorption, boost biomass production, and improve crop yields. In addition to increasing plant yields and growth, PGPF suppresses plant pathogens in the *rhizosphere* by producing plant hormones, hydrolytic enzymes, and mineral solubilization (N, P, and Fe). Other pathways include siderophore synthesis, saprophytic colonization competition, mycoparasitism, and the induction of systemic resistance.[8]

Various studies have emphasized the potential benefits of different fungi (Table 1). For example, *Phoma* sp. when inoculated, increased the fresh biomass and number of cucumbers,[9] while, *Aspergillus niger* and *Aspergillus caespitosus* enhanced content of protein, carbohydrate, total phenolic contents, anti-oxidant activity and diosgenin in *Trigonella foenum-graecum*.[10] *Aspergillus terreus* fungi have exhibited antifungal properties effects *Aspergillus fumigatus*, a human pathogen. Furthermore, in a study by Sarkar.[6] reported that *Trichoderma harzianum* TaK12 and *Trichoderma aureoviride* TaN16, both are phosphate solubilizing and IAA producing PGPF, enhanced the maximum shoot and root length of rice plants. Overall, the use of these fungi in sustainable agriculture practices offers promising solutions to reduce the reliance on chemical fertilizers and improve crop productivity. Few examples of PGPF are *Penicillium* sp., *Trichoderma* sp., *Pythium* sp.,[11] *Rhizoctonia oryzae*, *Aspergillus foetidus*, *Penicillium allahabadense*, *Daldinia eschscholtzii*, and *Sarocladium oryzae*,[12]

Table 1: Fungal strains as plant growth promoting fungi tested on different crop plants

PGPF	Test Plant	Effect on the Plant Growth
Penicillium sp.	*Pennisetum glaucum*, *Solanum melongena* and *Lycopersicon esculentum* seedlings	Enhanced seed germination and seedling vigour.[13]
Phoma sp.	*Cucumis sativus*	Increase in the plant biomass and length after 6 and 10 weeks of planting.[9]
Penicillium sp., *Pythium* sp., *Trichoderma* sp.	*Pennisetum glaucum*	Enhancement of seed germination, vigour and diseases protection against downy mildew of pearl millet.[11]
Aspergillus niger	*Trigonella foenum-*	Elevated levels of diosgenin, protein, carbohydrates,

and *Aspergillus caespitosus*	*graecum* seeds	and total phenolic content as well as antioxidant activity.[14]
Trichoderma harzianum and *Trichoderma aureoviride*	*Oryzae sativa*	Increased shoot and root length of rice plant.[6]
Aspergillus falvus, Aspergillusniger, Penicillium citrinum, Penicillium chrysogenum, and Trichoderma koningiopsis	*Triticum aestivum*	Systemic resistance to *Rhizoctoniasolani* induced.[15]
Gibberella intermedia	Waito-C *Oryzae sativa* germinals	Increase in the shoot growth by the production of gibberellins.[16]
Paraglomus occultum	*Lycopersicon esculentum*	Higher root and shoot length, shoot dry weight, yield as well as increased in potassium, calcium, Mgand Fe content.[17]
Penicillium pinophilum	*Lycopersicon esculentum*	Enhanced growth indices and fruit weights, significant reduction in disease incidence caused by Verticillium dahliae.[18]

Brief History of use of Fungi in Agriculture

The practice of Rhizobial inoculation in agriculture has a long history, spanning almost a century.[1-4,19] Microbes including fungi have been utilized for enhancing plant growth and combating both biotic and abiotic stresses. Roberts,[20] conducted pioneering research demonstrating the antagonistic interactions among microorganisms in aqueous environment, specifically highlighting the antagonistic relationship between *Penicillium glaucum* and bacteria. This work marked the inception of the term "Antagonism" as it pertains to the field of the microbiology. In the early 20th century, Hartley,[21] utilized 13 antagonistic fungi to control damping-off caused by *Pythium debaryanumin* forest nurseries. *Trichoderma* species were among the first PGPF recognized for their beneficial effects on plants. The recognition of *Trichoderma* species' potential as biocontrol agent of plant diseases dates back to the early 1930s. Over the years, numerous reports have been added to the list, documenting their effectiveness in controlling various diseases.[22] *Trichoderma lignorum* (*viride*) initially demonstrated the biocontrol potential against *Rhizoctonia solani*, and later the list expanded including other fungal pathogens such as *Rhizopus*, *Sclerotium rolfsii*, and *Pythium, Phytophthora.* Numerous studies have shown the value of antibiotics in biocontrol activities. For example, Weindling,[23,24] showed how *Trichoderma lignorum* could be used as a biocontrol agent to fight citrus seedling disease caused by the pathogen *Rhizoctonia solani*. Two years later it was reported that a strain of the same fungi produced a substance he called "gliotoxin," which acted as a "lethal principle" released into the surrounding medium, allowing the biocontrol agent to engage in parasitic activity. However, further investigation revealed that the fungus that produced gliotoxin was not *T. lignorum*, but rather another fungus called *Gliocladium virens*,[25] which was later reclassified as *Trichoderma* virens. During this foundational research period, many cases of successful biocontrol with PGPF species have been attributed to mechanisms such as mycoparasitism and/or antibiosis. During the 1960's, studies on mycorrhizal fungi began and soon various fungal strains were identified for plant growth promoting abilities with first fungal product (*Beauveria bassiana*) brought into the market named "Boverin" which was produced by the former Soviet Unionin the year 1965.[26] Howell and Stipanovic,[27] discovered and characterized a novel antibiotic, gliovirin, derived from *Gliocladium* (now *Trichoderma*) virens (GV-P), which exhibited potent inhibition against *Pythium* ultimum and certain Phytophthora species. This discovery has led to the commercial cultivation of various *Trichoderma* species for safeguarding and improving the growth of numerous of crops in the United States. *Penicillium bilaiae* has been created as a commercial formulation called Jumpstart® and produced to the market as a wettable powder in a number of countries.[28] In the recent years, many more fungal strains have been employed in the production of biofertilizers, pesticides, biocontrol agents.

Initiatives to Use PGPF Products in Agriculture System

Various countries have enacted policies to reduce reliance on chemical pesticides, fertilizers, and insecticides by promoting the development and use of biological alternatives. Japan's Ministry of Forestry, Fisheries, and Agriculture (JMAFF) synchronized its system with EPA Regulations in 1996. Similar to this, the European Pesticide Regulation EC No. 1107/2009 in Europe assesses biopesticides in order to promote the use of less hazardous materials by streamlining the registration procedure (2009/128/EC).[29] This shift along with the development of biopesticides and genetically modified crops, has led to a decline in the synthetic pesticides market over the past few decades.[10] Throughout the 1980s, partnerships such as those between the Nitrogen Fixation in Tropical Agriculture (NifTAL) and the United Nations Educational, Scientific, and Cultural Organization (UNESCO) have encouraged cooperation through Microbiological Resource Centers (MIRCENs) for the production of biofertilizer in Africa. In the United States, legislation such as: The Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), the Federal Food, Drug, and Cosmetic Act (FFDCA), and the Food Quality Protection Act (FFQPA) have a major impact on the rate at which biocontrol can enter the market and whether it remains there. On June 5, 2019, The European Commission ratified and implemented the EU Fertilizer Regulation (EC) No 2019/1009, which has replaced old Regulation (EC) No 2003/2003on July 16, 2022; broadened not only the scope of fertilizer to include mineral fertilizers and inorganic fertilizers, but also covering organic fertilizers, bio-stimulants and fertilizer made from such recycled materials. In October 2002, the Department of Agriculture; United States introduced the National Organic Program (NOP). This program includes only those organic products that comply with USDA regulations to be labelled as organic within the US.[10] In the European Union's implemented rules in 2018 paved the way for creating a regulatory framework for bioinoculants and regulating their sale on the internal market with CE mark, additionally steps were taken in 2020 to further refine this framework (https://blog.sathguru.com).

Government of India has taken several initiatives to encourage the adoption of organic farming and use of biofertilizer such as 'Paramparagat Krishi Vikas Yojana', 'Mission Organic Value Chain Development for North Eastern Region', 'National Food Security Mission and National Mission on Oilseeds and Oil Palm'. The nation produced 1,00,000.69 tons of carrier-based biofertilizers in 2021–2022 compared to 79,436.70 tons in 2019–20. (https://www.thehindusbusinessline.com). Besides this, in 2020, Govt. of India adopted a significant step by making it mandatory for every farmer purchasing urea to also buy biofertilizer. Due to these initiatives and the government's active promotion of safer and more sustainable farming practices, the Indian biofertilizer market is forecasted to experience a robust compound annual growth rate (CAGR) of 12.5% during 2023-2028 (www.fortunebusinessinsights.com). Another report has provided an extensive list of Indian manufacturers involved in the production of fungal bioinoculants.[7] In 2006, the Indian government included biofertilizers and organic fertilizers within the regulatory framework of the Fertilizer (Organic, Inorganic or Mixed) (Control) Order (FCO), 1985. Owing to these green inputs' substantial advantages over chemical alternatives, a number of government agencies, including the Department of Biotechnology, Ministry of Science and Technology, and the Ministry of Agriculture and Farmers Welfare, Govt. of India have actively supported the research, development, and marketing of these products.[30] Several manufacturers, including MD BiocoalsPvt. Ltd. Lovatde in Haryana, Multiplex Bio-Tech Pvt. Ltd. based in Karnataka, Ambika Biotech &Agro Services in Madhya Pradesh, Biotech International Limited in Delhi, and Shree Biocare India and Shree Biocare Solution Pvt. Ltd. in Gujarat, are actively involved in the production of fungal biofertilizer. In July 2019, ICAR introduced the technology for biofertilizers in a capsule form, named one-gram capsule containing microbial population equivalent to 1 kg pack of powder or a 1 litre bottle (www.fortunebusinessinsights.com). In India, the leading biofertilizer producers are Krishak

Bharti Cooperative Ltd (KRIBHCO) and Indian Farmers Fertilizer Cooperative (IFFCO), which are also the prominent players in the chemical fertilizer sector. Although the biofertilizer industry is still in nascent, there is ample opportunity for setting up more biofertilizer-producing facilities in the future. Currently, India already has more than 100 active biofertilizer facilities, and their capacity is rapidly increasing.[30] About 35 commercial companies and 32 integrated pest management (IPM) centers are receiving the necessary guidance and support from the Ministry of Agriculture and Farmers Welfare to manufacture biopesticides.[31] Many state departments of agriculture and horticulture in several states (Karnataka, Kerala, Uttar Pradesh, Gujarat, Tamil Nadu, and Andhra Pradesh) have set up numerous advanced biocontrol facilities in an effort to speed up the creation of screened prospective biocontrol agents. Microbial pesticide manufacture is also carried out by ICAR institutes and a small number of State Agricultural Universities. India now has 410 biopesticide production facilities, of which more than 130 are in the private sector[32] suggesting a growing interest and potential popularity of biopesticides and other biofertilizers. In contrast to the EU, which has appropriate quality standards and proof requirements for biostimulants, the US lacks a specific framework and fits biostimulants into the existing channels, which has resulted in exaggerated promises and a buyer beware atmosphere. Indian rules demand precise specification of the bio-stimulants, tolerance limits, and testing techniques have been set in order to prevent bogus claims, similar to the EU model (https://blog.sathguru.com).

Mechanism of Plant Growth Promotion by PGPF

The PGPF can enhance the plants growth through both direct and indirect methods (Fig. 1). Direct methods involve activity such asPhosphate solubilization (Fig. 2a) and production of indole 3-acetic acid (IAA). On the other hand, indirect methods encompass the production of siderophore (Fig. 2b), induced systemic resistance, and the ability to confer biotic and abiotic stress such as toleranceto heavy metal and salinity etc.

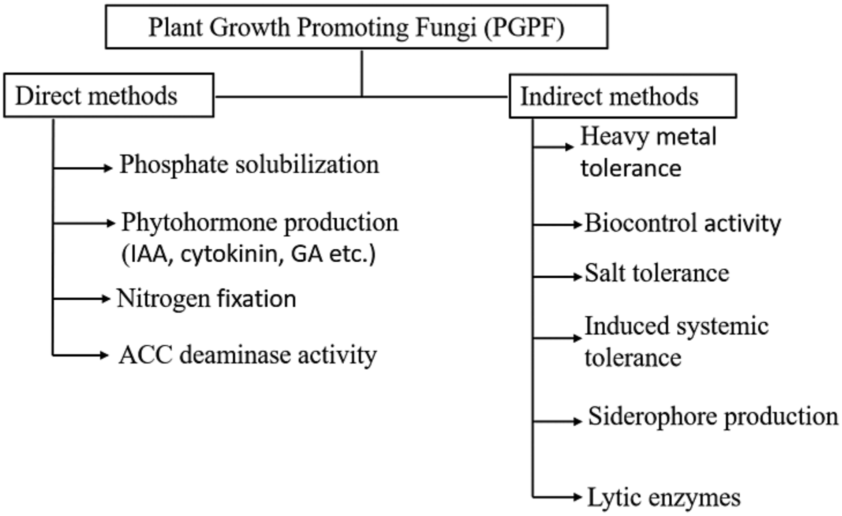

Fig. 1: Plant growth promoting fungi (PGPF) enhanced plant's growth by various direct and indirect methods

Phosphate Solubilizing Fungi

After nitrogen, phosphorus is the second most crucial mineral nutrient for plants in terms of quantitative requirement. While, soils contain a considerable amount of phosphorus in both organic and inorganic forms, its availability is limited due to its predominantly insoluble nature.[1,3,4] The effectiveness of applied phosphorus (P) fertilizers is typically limited to around 30% due to its fixation in soils. In acidic soil, P is fixed in the form of iron/aluminium phosphate, while, in neutral to alkaline soils, P fixation occurs in the form of calcium phosphate. These fixation processes hinder the availability of P for plants, leading to reduced efficiency of P fertilizers.[33] Like plant growth promoting bacteria, which solubilize the phosphate in the soil and make it available of the plant[2,3] certain fungal species also able to helps the plant growth by solubilizing the phosphate in the soil. Interestingly, when compared to bacteria, fungi seem to have more advantages as phosphate solubilizing microbes (PSM), as it can reach to spread up to large area around the plants root and make the nutrient available to the plant. Phosphate-solubilizing fungi (PSF) utilize three primary mechanisms to facilitate phosphate solubilization. These mechanisms encompass (a) the discharge of metabolites, (b) biochemical mineralization, and (c) biological mineralization. Solubilization of inorganic phosphorus by PSF mainly occurs by the release of organic acids (glycolic acid, oxalic, tartaric, and citric acid, formic acid, gluconic acid, and fumaric acid), whereas, organic phosphorus is solubilized by the release of various enzymes (phosphatases, phytases and phosphonatases). The PSF have specialized in solubilizing phosphate by releasing organic acids. These acids serve several functions, including (i) reducing pH levels, (ii) bolstering the chelation of cations, (iii) engaging in competition with P for soil adsorption sites, and or (iv) generating metal complexes alongside insoluble P elements like calcium (Ca), aluminium (Al), and iron (Fe). As a result, this process leads to the liberation of P.[1-4]

Indole- 3-Acetic Acid Production

Auxin is a plant hormone that exerts significant influence over various processes related to plant tissue formation, including growth, cell division, cell differentiation, and protein synthesis[1] and produced as secondary metabolites. Among the types of auxins, indole 3-acetic acid (IAA) plays a vital role in plant growth. Although plants produce a limited amount of endogenous IAA that is not directly utilized and the exogenous IAA derived from fungal isolation can be applied in biological fertilizers to enhance results and provide optimal benefits.[34] Fungi produce IAA from tryptophan (precursor of IAA) that is present in root exudates and releases it under a symbiotic association. In fungi, IAA synthesis can occur through two distinct pathways Trp-dependent and Trp-independent pathways with majority of studies concentrated on Trp-dependent pathways [(indole-3-acetamide (IAM), indole-3-pyruvic acid (IPyA) and tryptamine (TAM)].[35] The IAA synthesized by the fungi has the ability to stimulate the formation of lateral roots and the development of root hairs, ultimately leading to improved nutrient uptake by the plants associated with it. This, in turn, results in increased shoot or fruit biomass production. Many studies have been undertaken on IAA producing fungi that promote plants growth. For example, IAA producing fungi *Sordariomycetidae* sp. when tested on Arabidopsis thaliana enhanced lateral roots (3.1-fold).[36] Trigonella foenum seeds treated with mixture of PGPFs (*Aspergillus niger* and *Aspergillus caespitosus*) exhibited elevated levels of protein, carbohydrate, total phenolic, diosgenin content (342.374 $\mu g\ ml^{-1}$) and antioxidant activity, compared against individual PGPFs or distilled water.[14]

Siderophore Producing Fungi

The fourth most common element in the crust of the earth is ironand is essential to all living organism's processes of growth and development. It regulates the biosynthesis of several substances such as nucleic acids, porphyrins, antibiotics, siderophores, aromatic compounds, cytochromes, pigments, vitamins, and toxins.[37] Iron exists in two states in aqueous solution: Fe2+ and Fe3+. However, plants and microbes cannot use the Fe3+ form of iron because it forms insoluble hydroxides and oxides, which limits the iron's bioavailability. Microbes have devised various strategies for acquiring iron, one of which involves the utilization of siderophore to scavenge iron via specific receptor and transport systems. Siderophores are ferric ion chelators with a high affinity and low molecular weight,[3] that are excreted by few plants and aerobic microorganisms. They aid in overcoming iron insolubility by chelating with metal ions and facilitating their uptake inside the cell.[38] They are capable of forming very stable and soluble complexes with iron.[1-4] Microbial siderophores are recognized for their ability to bolster plant growth in condition of limited iron availability.[4] Fungal derived siderophores, characterized as potent iron-chelating compounds with high affinity, exists as linear to cyclic oligomeric secondary metabolites.[39] Unlike bacteria, fungi produce mostly hydroxamate type of siderophores with the exception of few fungi. So far, only two non-hydroxamate siderophores that have been identified and thoroughly studied to date. These include rhizoferrin, obtained from *Rhizopus microspores* and pistillarin, synthesized by the marine fungus *Penicillium* bilaii.[40] A Catechol type of siderophore is produced by *Rhizopus* sp. Many studies have been done to study the production of siderophore producing fungi (Table 1). Fungal hydroxamate siderophores have been categorized into three primary structural families including fusarinines, coprogens and ferrichromes. Fusarinineis known to be most common among the genera of *Aspergillus, Fusarium*, *Gliocladium*, and *Paecilomyces*.[41] Another siderophore ASP2397 derived from *Acremonium persicinum* MF-347833 considered to be a novel antifungal compound akin to ferrichrome. *Aspergillus niger* obtained from the *rhizosphere* zone of healthy cultivated *Viciafaba* plants produced a trihydroxymate siderophore, ferrichrome.[38] It has been reported that *Trichoderma harzianum* can produce maximum carboxylate and hydroxamate type of siderophore than another *Trichoderma* sp. like *T. asperellum,* T. *longibrachiatum*, and T. *viride*.[42] These siderophores have a strong binding strength for Fe (III), but they may also attach to other metals like as Pb (II), Cr (III), Al (III), and actinide ions. This suggests that they may find application in the bioremediation of heavy metal contamination, pharmaceuticals, and the management of industrial waste.

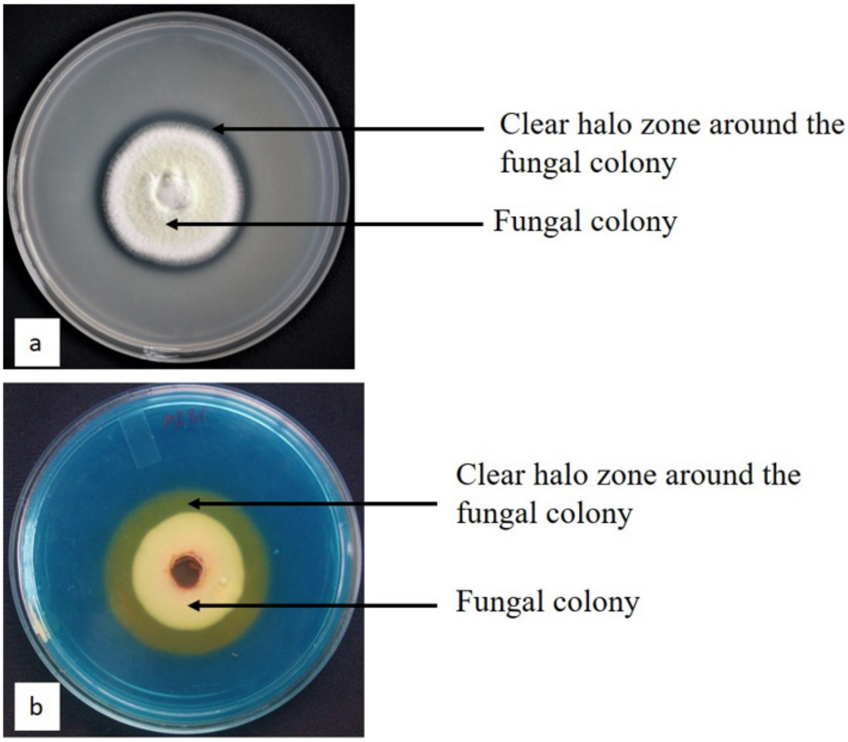

Fig. 2a: Phosphate solubilizing fungi forming halo zone around the colony on Pikovskaya's agar medium; b. Siderophore production by the fungal isolate on CAS agar medium. Formation of orange halo zone around the fungal colony indicates the siderophore production.

PGPF as Biocontrol Agents

Chemicals such as, pesticides, herbicides, fungicides etc. used in the agricultural system has affected environment and human lives to a great extent. They are known for endocrine disruption, antagonization of natural hormones in the body, immune suppression, reproductive abnormalities, hormone disruption, and cancer. Biocontrol agents (BCA) being the living organisms are used to fight against insects, phytopathogens, weeds, and pests. Certain fungal strains have proven to be a great substitute to conventional chemical pesticides and insecticides. Fungi can act as biocontrol agents (BCA) by different mechanisms such as direct antagonism (hyper parasitism), antibiosis, competition for micronutrients such as iron, mycoparasitism, hydrolytic enzymes, induced resistance, and *rhizosphere* competence.[43] The use of fungal strains has many benefits over the commercial harmful agrochemicals such as no development of resistance in the target, eco-friendly, renewable resource. Additionally, they exhibit a relatively rapid reproductive rate, encompassing both sexual and asexual processes, along with a brief generation time. They display specificity towards their targets. Furthermore, when devoid of a host, fungi possess the capability to endure within the surroundings by transitioning their parasitic behavior to saprotrophic nourishment, thereby upholding a state of sustainability. *Trichoderma harzianum* was the first fungal strain to be officially available as biocontrol agent in the market when it was listed in United States Environmental Protection Agency (EPA). In another study, the ability of PGPFs like *Aspergillus* falvus, *Aspergillus niger*, *Penicillium* citrinum, *Penicillium* chrysogenum, and *Trichoderma* koningiopsisfound to stimulate induced systemic resistance (ISR) in Triticum aestivum was compared to that of benzothiadiazole (BTH), a chemical inducer.[15] The results demonstrated that treatments with plant growth-promoting fungi (PGPF) resulted in the over-expression of the defensive genes, resulting in fewer disease symptoms when compared to both the BTH and the control group. Presently, the assessment of fruit loss after harvesting caused by phytopathogenic fungi is assessed to constitute over 50% overall agricultural fruit production; whereas, in India the post-harvest loss of fresh fruit and vegetables range from 4.6 to 15.9%.[43] Many fungal strains have been selected and tested for biocontrol agents *in vitro* and in the field condition. Entomopathogenic fungus *Beauveria bassiana* is employed to manage harmful insects, including white flies, thrips, mites, aphids, and their different life stages which cause damage to various crop plants.

Heavy Metal Tolerant Fungi

In modern agricultural practice, toxicity of heavy metals represents a significant abiotic stress that jeopardizes sustainable agriculture, diminishes crop productivity, and disruptsthe natural soil microbiota.[2-3] Soils contaminated by heavy metals as a consequence of mining activities are mostly covered only by sparse herbaceous vegetation with low productivity and species diversity. Various sources contribute to the presence of metals in the soil, encompassing activities such as fossil fuels combustion, mining and processing of metal-containing ores, disposal of municipal wastes, application of fertilizers and pesticides, utilization of sewage sludge as soil amendments, and the use of batteriesand pigments.[44] It is widely known that heavy metals cannot undergo chemical degradation and must either be physically extracted or immobilized. Various reclamation strategies are employed to repair the polluted site; but, when the concentration of the contamination is relatively low, they are either ineffective or highly expensive. Under these conditions, a revolutionary method called bioremediation—which restores soil by utilizing live creatures like microbes—is employed.[2-4] Numerous studies asserted that a variety of factors, including the combined influence of soil physical-chemical features and hazardous pollutants such heavy metals, are responsible for changes in the community structure of soil microbiota.[4] Because nutrients such accessible P, K, and organic matter encourage the proliferation and metabolism of microbes, which effectively reduces the heavy metal pollution, soil physio-chemical characteristics regulate the toxicity of heavy metals.[45] Mitigation of heavy metal toxicity in plants through ectomycorrhiza has been demonstrated in a number of experiments. Plant species, fungal species, and the kind of linked heavy metal are the main factors that determine how the AMF affects plants growing on contaminated media. However, the AMF increase plant resistance and heavy metal tolerance.[46] It has been demonstrated that *Diversispora spurcum* and *Funneliformis mosseae* diminish the amounts of zinc (Zn), lead (Pb), and cadmium (Cd) in the shoot of maize plants compared to the roots because they promote heavy metal accumulation in the subterranean portion of plants.[47] In the moderate dose of metal contamination, *Aspergillus* sp. was found to have a strong tolerance towards Cu, Pb, As, and Zn. In the severe level of heavy metal contamination, however, *Aspergillus* sp. showed a positive correlation with Ni and Cr.Therefore, it has been demonstrated that microbes associated with plant roots may affect the availability and uptake of heavy metals by plants in the *rhizosphere*.[75] However; this can only be achieved when the fungus can maintain the growth of its mycelium. Ultimately, this enhanced nutritional provision should result in improved health and growth of trees accompanied with the most resilient isolates.[48] In addition, a wide range of other extracellular materials are released by soil fungus, such as enzymes and organic acids (such as fumaric acid, citric acid, and gluconic acid) that can change the bioavailability and speciation of heavy metals in soil. They possess a few heavy metal (HM) tolerance mechanisms, including precipitation, mineral weathering, bio-absorption, volatilization, intracellular metal compartmentalization into fungal cell walls, and metal sequestration or accumulation.[49] Fungal oxidation can precipitate metals as insoluble metal oxalates, reducing metal bioavailability and increasing resistance to harmful metals.

Salt Tolerant PGPF

Microbes like fungi possess the capability to accumulate compatible solutes, which helps them counteract osmotic imbalance between their cytoplasm and the external environments. Additionally, they express various Na+ transporters to regulate and minimize cytoplasmic Na+ concentrations. In case of AMF, the tolerance to salt stress could be regulated by genes relatedto water-channel proteins (aquaporins), Δ1-pyrroline-carboxylate synthetase (LsP5CS); Na+/H+ antiporters, ABA (*Lsnced*) and late embryogenesis abundant protein (*LsLea*).50 The halo tolerant fungal strains can stand a very high level of salinity presenting its potential to help the plants grow in such harsh condition. They help the plants to acclimatize to the harsh environment by providing better acquisition of essentials nutrients (phosphorus, nitrogen, potassium etc.), inducing chemical and physiological changes. For example, less than 150 mM and 300 Mm of salt stress maize plants were inoculated with *Penicillium* chrysogenum, significant improvements were observed in various growth parameters compared to the group without it under both saline conditions. *Penicillium olsonii* cultured from the *rhizosphere* of tobacco plants enhanced the plant salt tolerance by increasing the levels of total chlorophyll, proline, CAT, and SOD activities.

Commercialization of PGPF Products

The market for PGPF based products has witnessed remarkable growth in the recent years observed by the increase in the demands for biopesticides, biofertilizers, and bio-stimulants derived from PGPF. The biofertilizer market is experiencing significant growth globally with countries such as Argentina, Canada, China, Europe, India and the United States leading the way as these nations have recognized the substantial advantages of biofertilizers and are actively promoting their adoption. The key drivers behind this growth are the rising awareness of sustainable agriculture practices, strict regulations in the chemical inputs, and the desire for organic and eco-friendly solutions. Global market of biofertilizers has been over serving significant gained in terms of profit. According to the estimates, the worldwide biofertilizers industry is projected to have a size of USD 2,314.30 million in 2023 and is anticipated to expand to USD 4,096.84 million by 2028, exhibiting a compound annual growth rate (CAGR) of 12.10% throughout the projected time frame of 2023-2028 (mordorintelligence.com). While, according to the report by Fortune Business Insights, the biofertilizer market in India is projected to experience a significant growth. The market is estimated to increase from USD 110.07 million in 2022 to USD 243.61 million by 2029, at a CAGR of 12.02% during the calculated period (www.fortunebusinessinsights.com). With the concern for the environment, most of the developed countries are moving towards the organic farming encouraging the uses of biofertilizers. However, to develop a reliable market products there are many aspects of the formulation to be considerate of. Whether a formulation is straightforward, cost-effective, and easily transportable or not, as it impacts both the duration of the product's shelf life and the methods of application on crops. Furthermore, deciding whether to manufacture the strains in liquid or solid form is an important consideration as they a significant role in determining the practicality and effectiveness of using the fungal strains as BCAs in agriculture system. Different types of formulations can be used such as granules, micro-granules, wettable powders, wettable/water-dispersible granules, dusts, biomass suspension in water, oils, and emulsions etc. The top consumers of fungal biofertilizers are Europe, America and Latin America because of the strict regulation these counties have applied to chemical fertilizers.[51] Also, the highest producers of bio-fungicides are USA and France.[52] Kiwa Bio-Tech Products Group Corporation, Lallemand Inc., Bayer CropScience, *Rizobacter,* and BASF SE are some of the key companies that manufacture biofertilizer in the global market. In 2012, the predominant bio-inoculants utilized were primarily *Rhizobium* (nitrogen fixing bacteria), accounting for 79% of the worldwide demand. In addition to other bio-inoculants such mycorrhizal products, phosphate-mobilizing bio-inoculants accounted for 15% of the market. N-fixing products now dominate the market, but demand for P-mobilizing products—including mycorrhizal—is predicted to rise. So far, there are approximately twelve manufacturers of mycorrhizal inoculums in the EU, distributed among countries like Germany, the UK, Spain, Czech Republic, France, and Switzerland and along with over 20 others globally with the majority located in the USA. Moreover, to boost more production of fungal agricultural products, the EU has initiated COST action to formulate a strategy in mycorrhizal technology. This will concentrate on the standardizing production techniques for AM fungal inoculums and establishing regulations to enhance soil quality and agricultural health. Mycotal (Verticillium lecanii), Biogreen (*Metarhiziumanisopliae*), *Trichoderma* 2000. (*Trichoderma harzianum*), Fusaclean (*Fusarium oxysporum*), Casst (*Alternaria cassia*), Luboa 2 (Colletotrichum gloeosporioides f. sp. cuscutae), Ketomium® (Chaetomium globosum and C. Cupreum), Promote® (*Trichoderma harzianum* and T. *viride*), SoilGard® (*Gliocladium virens*), AQ10 bio-fungicide (*Ampelomyces quisqualis*) are some of the PGPF product which has brought into the market.52-53 The share of the biopesticides in the market of Indian pesticides was a mere 4% in 2014. However, there has been a noteworthy growth in their usage, with biopesticides accounting for 9% of the overall pesticides' consumption in India by 2020, representing a significant increase of 40% between 2014 and 2019. So far, a total of 970 biopesticides has been registered by the central insecticides board registration committee (CIBRC). This suggests promising potential for fungi to serve as eco-friendly Argo-product on the times ahead.

Future Scope and Limitations

PGPF can play a significant role as biocontrol agents in an integrated agriculture management system.[15] They are microbes that aid in the solubilization, biological fixation, and mineralization of significant macro- and micro-elements that are necessary for plant good health. Even while tremendous advances have been achieved in our comprehension of interactions between plants and microbes on many different levels, there are still a number of gaps that must be filled in order to fully utilise the advantageous features. Commercial formulations are employed as biofertilizers and significantly contribute to the sustainability of agriculture, whether they are single-strained or utilised in consortia. In order to boost agricultural output, it is crucial to find novel strains, make existing strains more effective, and thoroughly research plant-microbe interactions.[54] The goal of future study should be to regulate microbial communities in rhizospheric soil in an integrated manner. The development of biotechnological and molecular methods will increase our comprehension of the cellular mechanisms and signalling pathways behind growth and DP resistance as an outcome of interactions between plants and microbes. Recent advancements in biotechnological tools and consistent modification may be helpful in creating the PGPF to give crop plants advantageous traits. Regular investigations on the genetic stability and ecological preservation of the genetically modified strain are required. One of the main problems with inoculants technology, however, is the survival of the microorganisms during storage. This survival is influenced by various factors, such as the growing medium and the physiological state of the bacteria at harvest, the process of dehydration, rate of drying, the temperature of storage and water activity of the inoculums.[55] Under normal storage settings, the inoculants' shelf life is reduced to three to six months as a result of all these factors. Therefore, research into extending the shelf life of inoculants or developing new carrier inoculants formulations is becoming more and more important.[56] It is essential to create efficient and useful methods for the mass cultivation, shipping, storage, formulation, and use of these fungi. What's more, work must be put into persuading the growers that PGPF might be a helpful supplement to their current crop management programmes. Use of biofertilizers, biopesticides, bio fungicides etc. has huge attention in the past few decades. Because of the potential of reducing the use of harmful agrochemicals government of many countries have already adapted the use such bioproducts. However, it is still at infancy stage. Many developed countries have already started to strictly regulate the application of chemical pesticides and fertilizers in an attempt to protect the environment. With harnessing genomic tools for PGPF selection, improvement in the formulation techniques and conducting field trials for evaluating long term effects it identifies future prospects. And also, many schemes have been initiated by the government to help the farmers to provide funds to encourage to opt for organic way of agriculture. Global markets and different companies have been trying their best to reduce the cost of production so that farmers can opt for sustainable product over the chemical products which are cheaper at the present time. In spite of the fact that numerous positive effects have been verified by experts around the world, nothing much is known about the significance of PGPF. Despite the potential benefits of PGPF several challenges hinder their widespread adoption in mainstream agriculture. Some of the limitations faced are as follows

a. Limitations such as Lower shelf life as the biofertilizers, contamination of the carrier material for the fungal biofertilizer also limits the efficiency of the biofertilizers.
b. Limited distribution of the biofertilizer among the farmers and in the market
c. Host specificity is another limitation of the PGPF as biofertilizer. Effect of climatic condition on the PGPPF, for instance one fungus can have certain optimum temperature requirement to be effective to enhance the plants growth.
d. Other constraints are the inconsistent response on different soils, crop and environmental conditions. There is no universal benchmark for bacterial and fungal viability or performance due to the natural diversity of these species and the flexibility of their roles.[53]
e. Also, the fraud companies selling fake products under the names of big companies create distrust among the farmers.
f. Difficulty in producing large quantities due to high production costs and an expensive data registration process that offers no legal protection.[23]

Conclusion

In conclusion, this review highlights the substantial contribution of PGPF in advancing sustainable agriculture practices. It underscores their potential to boost soil health, increase nutrient availability, and suppress plant diseases. Furthermore, review discusses the evolving market trends and identified potential challenges and future prospects associated with PGPF based products. Overall, the integration of PGPF into agricultural system holds promises for a more ecologically sound and economically viable approach to farming. The use of synthetic agrochemicals has had a significant and detrimental impact on the environment and human well-being. If this trend continues, a substantial portion of land will suffer from degradation, and there will be an increase in the occurrence of severe diseases affecting mankind. PGPF has proven to be a great substitute to pesticides and chemical fertilizers through many studies. However, still great deal of understanding is required to fully utilize the potential of PGPF in plants growth and development as application of PGPF depends on many factors such as abiotic factors, biotic factors, and formulation and combination of the fungal strains. Since many PGPF are host specific, deeper study on a single PGPF instead of studying only the superficial characters can also help a lot to get the proper manual of applying the particular PGPF into the field.

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Conflict of Interest

The authors do not have any conflict of interest.

Data availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethical Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Consent for Publication

All the authors have agreed to submit the paper to 'Current Agriculture Research Journal' for publication.

Author Contribution

- **Mum Tatung:** Formal analysis, writing original draft.
- **Anu Seng Chaupoo:** Formal analysis, writing original draft.
- **Chitta Ranjan Deb:** Conceptualization, Supervision, editing data and correction of manuscript.

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