Review Article

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Soil Application Of Plant Growth-Promoting Fungi: A Sustainable Strategy For Agriculture.

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ABSTRACT

PGPF (Plant Growth-Promoting Fungi) application is a revolutionary sustainable approach that enhances crop yields, improves soil health, and mitigates environmental degradation. PGPF interacts with plants, stimulating root growth, and boosting nutrient uptake, leading to improved crop productivity and quality. The fungal community also induces systemic resistance in plants through the expression of defence-related enzymes (such as peroxidase, polyphenol oxidase, and chalcone synthase) and defence chemicals (such as phytoalexin and anti-microbial phenolic compounds) for conferring structural and chemical barrier against pathogens and pests. Additionally, PGPF promotes soil biodiversity, structure, and fertility, increasing water retention and aeration. This approach reduces the reliance on chemical fertilizers and pesticides, minimizing soil pollution and environmental harm. By adopting PGPF application, farmers can achieve sustainable agriculture, ensuring food security and environmental conservation.

Keywords
Mycoparasitism, Phytohormones, Plant Growth-Promoting Fungi, Rhizosphere Sustainable Agriculture, Systemic Resistance.

INTRODUCTION

PGPF are a heterogeneous group of soil-dwelling, non-pathogenic saprophytic fungi that establish a close association with plants and promote plant growth and health through several activities (Naziya *et al.*, 2020). Further, fungi under PGPF may differ distinctly from each other with respect to their taxonomy, habitats, physiology, and even to their interactions with plants. The term PGPF is not absolute, rather it is an operational term (Bent, 2006), as all fungi that promote plant growth are not PGPF, for example, mycorrhizal fungi, which are known to boost the growth of the plants, are not considered as PGPF. An important feature that gives PGPF a different identity is that the they are non-symbiotic saprotrophic fungi that live freely on a zone of soil at the vicinity of the root or the interior of the root itself, whereas mycorrhizal fungi behave as obligate biotrophs and develop an intimate association with the roots of most host plants (Hossain *et al*., 2017a, b). Root colonization ability is considered as one of the most important characteristics of PGPF which helps to promote plant growth (Islam *et al*., 2014). Fungi of the genera such as *Aspergillus, Fusarium, Penicillium, Piriformospora, Phytophthora, Rhizoctonia, Phoma*, and *Trichoderma* are the strains mostly used in research as PGPF (Hossain *et al*., 2017a, b; Javaid et al., 2020; Murali et al., 2021). The non-pathogenic fungi such as *Pythium oligandrum* and *Phytophthora cryptogea* colonizing the root ecosystems are also considered as PGPF (Benhamou *et al*., 2012; Bent 2006). PGP fungi have reported from different genera of phyla Chytridiomycota, Zygomycota, Glomeromycota, Ascomycota, and Basidiomycota. The beneficial effects of Plant Growth-Promoting Fungi (PGPF) are linked to their ability to colonize roots, produce growth hormones, facilitate mineralization, enhance nutrient uptake, control diseases through antagonistic mechanisms, and trigger defense strategies against pathogens. These defense strategies include inducing systemic resistance (ISR) and systemic acquired resistance (SAR) in plants, which involves the production of defense enzymes, chemicals, and pathogenesis-related proteins (PR-proteins) (Islam *et al*., 2014; Nogueira-Lopez *et al.*, 2020). The beneficial fungi promote the plant via directed multifarious plant growth-promoting (PGP) attributes like micronutrients solubilization (phosphorus, potassium and zinc) and production of plant growth regulators like auxin, gibberellins, cytokinin and ethylene or indirectly via the antagonistic substances, production of siderophores, antibiotic and synthesis of cell wall lysing enzymes like cellulases, glycosidase and gluconase (Abo Nouh, 2019; Urja and Meenu, 2010). By harnessing the benefits of beneficial soil microorganisms, including fungi, soil health can be substantially enhanced, diseases can be controlled through antagonistic interactions and induced systemic resistance, plant growth can be promoted, and a more sustainable alternative to synthetic chemical fertilizers can be provided (Bhardwaj *et al*., 2014). These prospective PGPF would play an important role in agriculture for long-term productivity, soil health management, and environmental restoration as a cost-effective input in the next decades, perhaps providing substantial relief for food security.

Rhizosphere

Rhizosphere is the soil zone, which is influenced by the roots. Plants share a micro-ecosystem at the vicinity of the plant root system comprising hot spot zone of the microbial community (like bacteria, fungi, nematodes, viruses, arthropods, oomycetes, protozoa, algae, and archaea), of which bacteria and fungi are most common and extensively studied (Akinola and Babalola 2021). The plant rhizosphere harbours both beneficial and pathogenic microorganisms comprising up to 1011 microbes per gram of soil and above 3000 prokaryotic species in general; and therefore, it represents a composite ecosystem on earth (Hossain et al., 2017a, b; Mendes et al., 2013). This rhizospheric zone offers great opportunities for plant–microbial interactions, and therefore significantly affects plant growth, disease resistance, and nutrient recycling (Akinola and Babalola, 2021). Understanding the complex microbial interactions in the rhizosphere is essential for developing organic farming practices that reduce reliance on synthetic chemical fertilizers, which can harm the environment and surrounding ecosystems (Rascovan et al., 2016).

1.1 Plant Growth Promotional Activities of PGPF

The plant growth promotional activities of PGPF are attributed to the production of plant growth hormone and mineralization and as such many more. Research has consistently shown that PGPF play a significant role in enhancing various aspects of plant growth and development, including seed germination, seedling vigor, shoot and root growth, photosynthetic efficiency, flowering, and ultimately, crop yield (Hossain and Sultana, 2020)

Production of Plant Growth Hormone

Plant growth hormones also called phytohormones help to regulate the growth of the plants through various developmental processes. Phytohormones, specifically auxins (IAA), gibberellins, and cytokinin can exogenously produce by Plant Growth-Promoting Fungi (PGPF) and play a pivotal role in regulating plant growth and development. IAA and gibberellins are particularly significant, as they induce crucial physiological responses during various stages of plant growth (Islam et al., 2014). The production of IAA, a highly important and widely distributed phytohormone, has been reported in several fungi, including Trichoderma, Penicillium, Aspergillus, Fusarium, Talaromyces, and Mortierella, in host plants such as chickpea, rice, and wheat, resulting in enhanced growth and yield (Abri et al., 2015; Kumar et al., 2017; Murali et al., 2021). Gibberellic acid (GA) is a phytohormone of significance, produced by various fungi, including Fusarium, Aspergillus, and Penicillium, which contributes substantially to plant growth and developmental processes, in addition to conferring tolerance to abiotic stress (Syamsia et al., 2021). Notably, the GA produced by Cladosporium species in wheat and cucumber plants has been demonstrated to enhance plant growth (Hamayun et al., 2010). Moreover, endophytic fungi, such as Penicillium citrinum and Aspergillus fumigatus, have been reported to promote plant growth by secreting GAs in the rhizosphere, thereby stimulating plant development and growth (Ahmad et al., 2010). Another important plant growth regulator, cytokinin (predominantly zeatin), elicited by Piriformospora spp., Phoma spp., and Trichoderma spp. caused growth promotion in melon and Arabidopsis (Martínez-Medina et al., 2014; (Hossain and Sultana 2020; Speakman and Kruger 1984).

Mineralization

Mineral availability in the rhizosphere is controlled by combined effects of soil properties, plant characteristics, and root-microorganism interactions (Jones et al., 2004; Rengel and Marschner, 2005). Rhizospheric fungi can enhance mineral uptake and availability, compensating for deficiencies through their symbiotic relationship with plant roots.

Phosphorous Solubilization

Plant Growth-Promoting Fungi (PGPF) in the rhizosphere significantly increase phosphorus (P) availability for plants by solubilizing phosphate compounds. Research has shown that Phosphate-Solubilizing Fungi (PSF) can convert insoluble phosphate into soluble forms, providing a promising alternative to phosphorus fertilizers (Alam et al., 2002; Chabot et al., 1996; Pal 1998). The fungi achieve this by producing various organic acids like tartaric acid, succinic acid, oxalic acid, malic acid, 2-ketogluconic acid, glyoxylic acid, gluconic acid, fumaric acid, citric acid and alpha-ketobutyric acid and enzyme phosphatase (Devi et al., 2020). All the release compounds solubilize the phosphorus and avail the soluble inorganic form that can be assimilated by the plants. A number of fungal species including P. bilaji, Penicillium spp. (Patil et al. 2012), P. oxalicum (Li et al. 2016a) Aspergillus niger, Penicillium notatum (Din et al. 2019; Malviya et al. 2011), Aspergillus awamori (Jain et al. 2012a), Penicillium bilaii (Ram et al. 2015), Trichosporon beigelii, Rhodotrula aurantiaca, Cryptococcus luteolus, Zygoascus hellenicus, P. purpurogenum var. rubrisclerotium, Neosartorya fisheri, and Candida montana (Gizaw et al. 2017), Talaromyces aurantiacus, Aspergillus neoniger (Zhang et al. 2018a), and Trichoderma spp. (Bononi et al. 2020) have been reported for the solubilization of phosphorus. Rhizospheric fungi Penicillium, Aspergillus, Trichoderma, Phoma, Rhizoctonia, Rhizopus, and Alternaria have been documented for their efficiency in solubilizing the insoluble phosphate (Alori et al., 2017; Dotaniya and Meena 2015). For the potassium solubilizination we can use large amount of microorganism like as Aspergillus spp., Agrobacterium tumefaciens, B. pumilus, B. subtilis, B. circulans, B. edaphicus, B. mucilaginosus, Flavobacterium spp. and Rhizobium spp. (Gundala et al. 2013; Keshavarz Zarjani et al. 2013; Maurya et al. 2015; Meena et al. 2014a; Meena et al. 2014b). This potash- solubilizing biofertilizer can be applied in crop production and yield combination with potassium solubilizing microbiome are Azospririllium, Azotobacter, Azospirillum, Acetobacter and Rhizobium (Bahadur et al. 2016). Among the PGPF, different Trichoderma strains have been exploited to enhance mineralization and mineral absorption of Fe, N, P, and K, and increase the accessibility of ammonium, nitrogen, zinc, copper, iron, and manganese (Molla et al., 2012).

1.2 Management of Disease

The use of Plant Growth-Promoting Fungi (PGPF) in plants is environmentally friendly approach to manage diseases, which triggers a long-lasting activation of innate immunity of plants. Apart from promoting plant growth, PGPF employs various strategies to protect plants from pathogens by inducing defence resistance. The primary mechanism of PGPF in sustainable disease management involves colonizing plant roots, facilitating nutrient uptake, and stimulating plant growth (Hossain et al., 2017a, b; Murali et al., 2013). The key disease management strategies employed by PGPF can be summarized as follows:

Antagonism

The bio-control mechanism against disease-causing pathogens can be achieved through the antagonistic efficacy of microorganisms. PGPF exerts its bio-control mechanism through multiple strategies, including antibiosis, competition, and parasitism. Antibiosis occurs through the production of antibiotics and biosurfactants, which inhibit pathogen growth. Competition ensues as PGPF competes with pathogens for colonization sites, nutrients, and minerals. Additionally, PGPF produces extracellular cell wall-degrading enzymes, such as chitinase and β-1,3-glucanase, which break down pathogen cell walls, ultimately reducing damage to plants (Berg et al., 2005). Different PGPF, namely, Trichoderma, Gliocladium virens, Phoma sp., Fusarium equiseti, and Penicillium simplicissimum have been reported to be antagonistic against Rhizoctonia solani, Pythium aphanidermatum, Pythium irregulare, Sclerotium rolfsii, Fusarium oxysporum, Pseudomonas syringae, and Colletotrichum orbiculare (Lewis et al., 1998; Murali et al., 2021). Patale and Mukadam (2011) have successfully tested the antagonistic activity of Trichoderma viride and Trichoderma harzianum against seven pathogenic fungi, namely, Aspergillus niger, A. flavus, Phytophthora spp., Fusarium oxysporum, Rhizoctonia solani, Penicillium notatum, and Alternaria solani. Gliovirin, an antibiotic produced by Gliocladium virens, was shown to inhibit the growth of Pythium ultimum (Howell and Stipanovic 1983).

PGPF and induced resistance

Induced resistance is triggered by pathogens or insects, activating defensive compounds. It has two categories: Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR). ISR is activated through the jasmonate pathway (Cong and Lingyun, 2019), triggered by pathogens, drought, herbivores, and mechanical injuries. SAR is regulated by the salicylic acid-dependent signaling pathway, involving local and systemic increases in salicylic acid, leading to the promotion of pathogenesis-related proteins (Backer et al., 2019). PGPF can elevate plant's defence against insects and diseases by triggering resistance or activating natural defence responses (Adesemoye and Kloepper, 2009). The level of induced resistance in plants can vary depending on factors such as the source, type, and intensity of stimuli (Aranega-Bou et al., 2014). Trichoderma strains inoculated to the rhizosphere protect host plants against numerous pathogens including bacteria, and fungi, due to the induction of resistance responses similar to the hypersensitive mechanism, SAR and ISR in plants (Singh et al. 2016; Jyoti et al., 2014), as peroxidase reactive oxygen species (ROS) activity was triggered by T. virens in cotton plants reported by Singh et al. (2016).The use of non-pathogenic strains of F. oxysporum to control wilt disease has been detected for many crops (Ahmad et al., 2018). Pythium oligandrum has shown the ability to control soil-borne phytopathogens either in the laboratory or in the field. P. oligandrum oospores have been used as seed treatments that reduce damping-off disease in sugarbeet caused by P. ultimum (Rocha et al., 2019). Also, P. nunn is an antagonistic fungus or mycoparasite of pathogens such as Pythium ultimum, P. aphanidermatum P. vexans, Rhizoctonia

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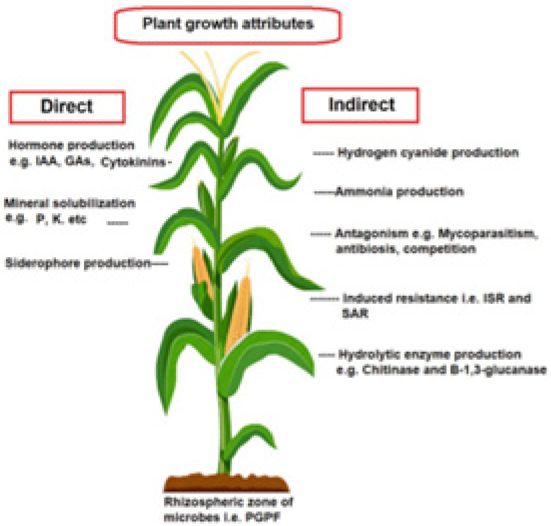
solani, Phytophthora parasitica, and P. cinnamomi. Moreover, Aspergillus and Penicillium species were effective against the white-rot disease caused by basidiomycetes (Kowalczyk et al., 2019).

Penicillium oxalicum, a plant growth promoting fungus (PGPF) isolated from pearl millet rhizosphere soil, exhibited a considerable increase in chitinase activity (Murali and Amruthesh 2015). Trichoderma atroviride TRS25 increased PPO and PAL enzyme activity when the cucumber plant was inoculated with Rhizoctonia solani (Nawrocka et al., 2018). Trichoderma spp. is widely studied for their role in controlling the phytopathogen by the production of cell wall degrading enzymes such as cellulases, chitinases, and glucanases (Nogueira-Lopez et al., 2020).

Figure 1: PGPF in contributing overall growth of the plant through direct and indirect mechanisms (Mandal P and Tiru Z, 2024).



Bioformulations

Biocontrol agents (bio-agent) comprising fungi have become attractive in terms of sustainable management of diseases and improved quality of crop productivity (Hussain et al., 2020). The antagonistic property of PGPF can be successfully exploited through proper identification of efficient bio-control agents, their multiplication, and formulation for delivery. A large number of bio-based products are being produced and sold worldwide in the form of granules, wettable powders, dusts, and aqueous or oil-based liquid products using different carriers to control fungal pathogens (Ardakani et al., 2009; Nega 2014). The application of Trichoderma-based bio-fertilizer (composted of cattle manure + inoculum) not only produced the antifungal compound which may suppress the pathogen but potentially improved grassland biomass (Zhang et al., 2018). Bio-organic fertilizers (BOFs) enriched with Trichoderma and animal manure have been found not only to cause plant growth promotion but also found to have the controlling effect against Fusarium wilt in cucumber plants (Chen et al., 2011; Zhang et al., 2013, 2016). The foliar sprays of the liquid formulation of Penicillium oxalicum (6 X 106 CFU ml−1) with sodium alginate (0.5%) and Tween 80 (0.01%) substantially improved the yield and acted as biofungicide for controlling mango malformation (Haggag and El Soud, 2013).

1.3 Abiotic Stress Management

Plant growth promoting fungi (PGPF) are recognised for alleviating a variety of abiotic challenges (heavy metal stress, water stress, temperature stress, and salt stress). Penicillium species isolated from groudnut rhizosphere soil were reported to improve salinity tolerance in sesame plants, as well as disease resistance and plant growth promotion (Radhakrishnan et al., 2014). Trichoderma harzianum promotes root growth and aids in water absorption and nutrient intake during osmotic stress. Distinct strain of Trichoderma has been carefully studied for its ability to mitigate oxidative, salinity, drought, and osmotic stress in plants (Zaidi et al., 2014). Microsphaeropsis, Mucor, Steganosporium, Phoma, Aspergillus, Alternaria, and Peyronellaea have been shown to protect Arabidopsis plants from heavy metal buildup (Murali et al., 2021). Trichoderma has been reported to assist plants increase the activity of antioxidant enzymes, hence protecting plants from ROS production and membrane damage in stressful conditions (Guler et al., 2016).

Conclusion and Future Prospects

Unlocking the benefits of Plant Growth-Promoting Fungi (PGPF) is crucial for developing innovative strategies to enhance crop yields and effectively manage crop diseases, leading to improved agricultural productivity and sustainability. Despite their potential, Plant Growth-Promoting Fungi (PGPF) face challenges in practical applications due to inconsistent performance, likely caused by genetic, environmental, and other factors. In order to popularize the widespread use of PGPF, the development of some innovative and effective techniques for their mass culture, formulation, and application of these fungi are urgently needed to be addressed. Advanced molecular tools and techniques can give more insight into mechanisms and outcomes of plant-microbial interactions. Additionally, biotechnological innovations, such as genetic modification and gene transfer, can enhance PGPF's benefits, leading to more promising and effective solutions for widespread adoption. PGPFs are successfully used in many countries, but some still rely on chemical fungicides. Addressing challenges and limitations is crucial to promote wider adoption and sustainable agriculture.

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