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Piriformospora indica: A novel endophytic fungus bridging plant growth and stress resilience

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Abstract

In Eco communities, plants interact with a diverse spectrum of microorganisms through intricate symbiotic relationships. In mutualistic relationships, the fungus provides the plant with support in the form of increased growth promotion, a stronger resistance to biotic and abiotic stress, etc. A fungus belonging to the Sebaciniales order is called *Piriformospora indica*, discovered from orchid plants in the Thar desert in Rajasthan, India by Prof. Ajit Verma and group. The single endophytic root-colonizing species, *Piriformospora indica*, is the only member of this monotypic genus. Many different types of vascular plants become colonized by the fungus, which boosts the plants' growth, seed production, and resistance to both biotic and abiotic challenges. *P. indica* is easily grown on a variety of substrates. During its mutualistic symbiotic interaction with a wide range of plants, it has been discovered to stimulate plant development. *P. indica* grows more readily on a variety of substrates, such as complex or synthetic medium, than AM fungi do. Plant-microbe interactions can be studied using this fungus as a model organism and as a new tool to enhance plant production systems because of its easy culture.

Keywords: *Piriformospora indica*, endophytic fungi, plant growth promoter

Introduction

Many microorganisms in natural environments interact with plants in an attempt to gather nutrients for their existence. These interactions can be neutral, damaging (parasitism), or advantageous (mutualism or symbiosis) to the host. A novel fungal isolate was found in an arbuscular mycorrhizal fungal spore that was found in Indian desert soil by Dr. Ajit Verma in 1998^[62]. It was simple to grow on a variety of synthetic medium and produced chlamydospores in the shape of pears. The fungus invaded the root cortex of maize, as demonstrated by inoculation (A. Verma, *et al.* 1999)^[60]. Based on appearance and ultrastructure, it did not resemble any known fungus, leading to the description of a new genus. The isolate was given the name *Piriformospora indica* because of its distinctive spore structure (S. Verma, *et al.* 1998)^[62]. This fungus, which resembles a mycorrhiza, can ally with roots to promote plant growth and development (A. Verma, *et al.* 1999)^[60] (Bagde, Prasad and Varma 2013)^[8, 40, 61]. The general biomass output of a wide range of plants was positively impacted by *P. indica* inoculation, and further investigations revealed that *P. indica* has a number of physiological impacts. (A. Verma, *et al.* 1999)^[60]. *P. indica* is easier to grow on a variety of specified synthetic medium than AM fungi, and it promotes the growth of plant biomass in a wide range of plant species, including ferns, angiosperms, and gymnosperms. Plants have utilized *P. indica* to boost biomass growth, improve nutrient uptake, increase resistance to diseases, and enhance secondary metabolites. *P. indica* root endophyte has also been convincingly shown to reduce the need for artificial fertilizers, regulate agricultural productivity, and enhance plant resistance to both biotic and abiotic stressors. According to reports, *P. indica* has significant growth-promoting properties, a high tolerance to salt, and resilience to disease, all of which increase the yield of the host plant (Kumar, *et al.* 2009)^[30].

2. Characteristics features of *P. indica*

According to A.verma and team, *Pririformospora indica* can be easily grown on various type of complex and substrates. where it asexually forms 8 to 25 nuclei per spore. Stages of a sexual life

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cycle have been not observed. In the initial stages of plant root colonization, *P. indica* invades living plant cells (Jacobs, *et al.* 2011) [26]. Although minor zonation's were observed in other cultures, were observed in other cultures, young mycelia were white and nearly hyaline. The majority of the mycelium was flat and immersed in the substrate. Hyphae had thin walls and varied in diameter from 0.7 to 3.5 μ m (Huong Pham, *et al.* 2008) [25]. The hyphae were irregularly septated and frequently displayed anastomoses. They frequently overlapped and entangled with one another. Hyphae were frequently irregularly inflated, exhibiting a nodose to coralloid shape, and granulated thick masses were seen in older cultures and on the root surface (Huong Pham, *et al.* 2008) [25]. Multiple nuclei were present in many cells. The hyphae's tips developed thin-walled vesicles that gave rise to chlamydospores. The walls of very immature spores were thin and hyaline. When fully grown, these spores possessed smooth, two-layered, pale-yellow walls that were up to 1.5 μ m thick. Sexual structures and clamp connections were not seen (Huong Pham, *et al.* 2008) [25]. This initial stage is followed by the death of colonized cells even though the plant host displays no macroscopic signs of disease (Deshmukh, *et al.* 2006) [16]. A plant-derived membrane that envelops and isolates *P. indica* hyphae from the plant cytoplasm has been seen during the early stages of the interaction (Jacobs, *et al.* 2011) (Lahrman and Zuccaro 2012) [26, 31]. The structural configuration of this connection is comparable to that of AM fungi's arbuscular and transcellular hyphae, which are both equally encircled by a perifungal membrane (Bonfante and Genre 2010) [12]. Although *P. indica* is a basidiomycete that has many characteristics with arbuscular mycorrhizal fungus, it is classified under the new order Sebaciniales-Gloriomycota and the new family Sebacinaceae (A. Verma, *et al.* 1999) [60]. The fungus has enormous potential to increase crop yield and tolerance, particularly in the current period of shifting weather patterns. Because of this, *P. indica* is regarded as a potent symbiont candidate for enhancing crop output and plant development in agroforestry, floriculture, and sustainable agriculture.



Fig.1: Mycelium Growth of *P. indica*, grown on solidified MYP medium after 8 days

3. Cultivation of *P. indica*

The fungus *Piriformospora indica*, which promotes plant growth, interacts mutualistically with a variety of angiosperms, including both dicot and monocot plants. This fungus produces thick-walled, pear-shaped chlamydospores that can be stored at ambient temperature for about a year. The primary benefit of *P. indica* over AM fungi is its ability to grow axenically on a

variety of synthetic solidified and broth media, including Aspergillus, Modified Aspergillus Medium, Potato Dextrose Agar, Woody Plant Medium, and yeast extract mannitol peptone agar, Malt Extract, M4N, Czapek's Dox Agar, Modified Melin-Norkrans, MS, and MYP (Singh, *et al.* 2013) [53]. On a solid agar media, *P. indica* mycelium creates rhythmic circles. Both mycelium and chlamydospores can spread it. Aspergillus was the most effective of the studied medium (Hill and Kafer 2001) [23]. In order to lower the cost of medium, a recent study suggests replacing Hill and Kafer medium with Safal Jaggery medium, an inexpensive and locally available nutritional source of energy. It can compete with Hill and Kafer both commercially and quantitatively (Attri and Verma 2018) [6, 23].

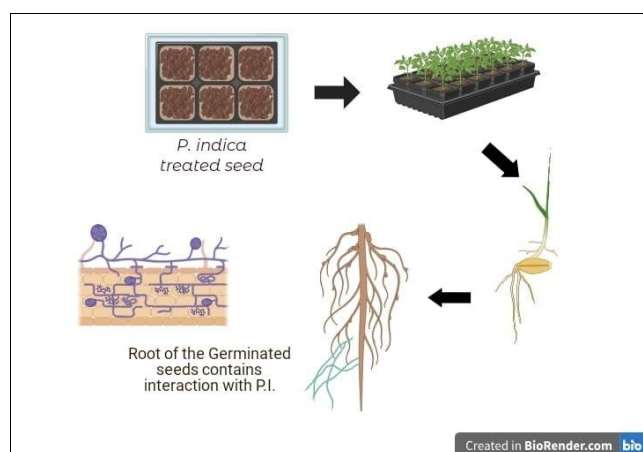


Fig 2: Maintenance of *P. indica* in potato dextrose containing broth media.

4. Root interaction of *P. indica* with plants

P. indica's beneficial benefits were caused by its interactions with plants. A wide variety of mono- and dicotyledonous plants, including significant crop plants, have their roots colonised by it. According to another study, *P. indica* colonises barley roots by allowing fungal hyphae to infiltrate through the root hairs of older plants (Vadassery and Oelmüller 2009) [57]. This root endophyte can only grow in the root's cortical tissue, primarily in the root hair zone and differentiation (Deshmukh, *et al.* 2006) [16]. Chlamydospores start colonisation, and as they germinate, they eventually develop a network of hyphae on and within the root. Through the intercellular gaps, hyphae enter the subepidermal layer, where they branch and proliferate (Deshmukh, *et al.* 2006) [16]. Fungal hyphae overtook rhizodermal and cortical cells in later colonisation stages. In several instances, a thick network of fungal hyphae coated the protoplasts, obscuring the transverse cell walls of nearby cortical cells (Vadassery and Oelmüller 2009) [57]. Additionally, the fungus entered the basal regions of the root hair cells, where

branching hyphae produce a lot of chlamydospores that begin at the base of the root hair and continue until the root hair is filled with a stack of spores.



5. The biotechnological uses of *P. indica*

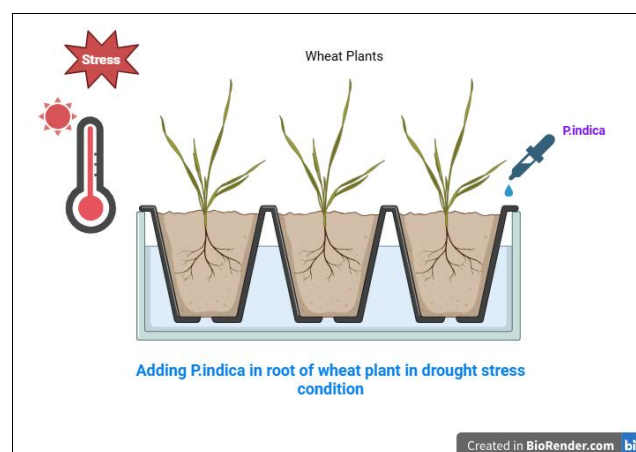
Enhancing nutrient intake, enabling plants to withstand water, temperature, and salt stress, providing (systemic) resistance to toxins, heavy metal ions, and pathogenic organisms, and promoting growth and seed production are all benefits of the endophyte (A. Verma, *et al.* 1999) [60]. *P. indica* is an intriguing endophytic fungus that can live on the roots of any plant on the planet and establish a symbiotic connection with it. Additionally, *P. indica* has been demonstrated to boost plant defence against root infections and crop productivity in a range of crops, including barley, tomato, and maize (Deshmukh, *et al.* 2006) (A. Verma, *et al.* 1999) [16, 60].

6. Role in Abiotic Stress Tolerance

6.1 Drought stress

Drought stress has a significant impact on plant growth, and in order to live, plants must adapt to this stress. There are various categories of drought resistance systems. Drought escape, which includes plants that finish their lifecycles during the wet season, before the onset of drought, and the only true drought avoiders, can be separated from desiccation postponement, which is the ability to maintain tissue hydration, and desiccation tolerance, which is the ability to function when dehydrated. These are sometimes referred to as drought tolerance at high and low water potentials, respectively. Plants under drought stress undergo a variety of physiological and biochemical reactions, including stomatal closure (Schroeder, Kwak and Allen 2001) [46]. Since *P. indica* was discovered from a desert, it is probable that the fungus could help plants withstand dryness. Chinese cabbage and Arabidopsis are two examples of plants that *P. indica* effectively gives resistance to abiotic stressors, such as drought tolerance (Sherameti, Tripathi, *et al.* 2008) [51]. The fungus *P. indica* co-cultivated seedlings of Arabidopsis continue to thrive when subjected to mild drought stress, whereas the uncolonized controls do not and exhibit withering symptoms (Sherameti, *et al.* 2005) [50]. While untreated controls showed growth inhibition, fungal-colonized Arabidopsis plants exposed to stress demonstrated greater drought tolerance and continuous growth (Sherameti, Tripathi, *et al.* 2008) [51]. Under drought stress, fungus-colonized plants showed higher levels of chlorophyll and higher photosynthetic efficiencies than uncolonized plants (Sherameti, Tripathi, *et al.* 2008) [51]. By stimulating the expression of a wide range of stress-related genes in the leaves, *P. indica* gives Arabidopsis the ability to

withstand drought stress. Many colonised seedlings reach the blooming stage and produce seeds after being first exposed to drought stress and then moved to soil, whereas the percentage of uncolonized seedlings that do the same is significantly lower (Jacobs, *et al.* 2011) (Sherameti, Tripathi, *et al.* 2008) [26, 51].



6.2 Salt Stress

Many different types of monocots and dicots are colonised by *P. indica*. communicate a number of advantages to host plants, such as wheat, including enhanced plant health through higher growth performance under both normal and stressful conditions, and better tolerance to a variety of biotic and abiotic challenges. Plants and beneficial fungi, like *P. indica*, can coexist in symbiotic relationships that change secondary metabolism, encourage growth, lessen the effects of abiotic stressors, and increase plant fitness by modifying stress tolerance mechanisms. *P. indica* activated the antioxidant metabolism, which results in the formation of ascorbate, and contributed nutritional and salt resistance to the co-cultivated tomato plants (*Solanum lycopersicum* "Roma"). The lycopene content of the *P. indica*-inoculated plant's fruits remained constant despite the growth conditions (Aruna, *et al.* 2023) [4]. The development and production of tomato plants are positively impacted by *P. indica* colonisation, while plant productivity is adversely affected by drought stress, with the impact becoming more severe as irrigation levels are decreased (Aruna, *et al.* 2023) [4]. According to a study, *P. indica* promotes development by stimulating nitrogen buildup in the roots of tobacco and Arabidopsis seedlings by activating nitrate reductase and the enzyme glucan-water dikinase (SEX1), which breaks down starch (Sherameti, Shahollari, *et al.* 2005) [48, 50]. Additionally, *P. indica* has been shown to enhance tomato colonization's nitrogen acquisition, which promotes host growth and development (Cruz, Feghhi and Martins-Loução 2013) [13].

6.3 Heat Stress

Although *P. indica* has been shown to have some effect on increasing plant heat tolerance, nothing is known about how it does so and its exact processes are still unknown (Rajput, *et al.* 2022) [2]. According to preliminary research, *P. indica* may improve plant heat tolerance in a number of ways. First of all, it increases the plant's antioxidant enzyme system's activity, reducing oxidative stress brought on by high temperatures (Li, *et al.* 2023) [1]. Second, it might control plant hormone levels, which would enhance growth circumstances and the plants' capacity to tolerate extreme temperatures (Bhuyan, *et al.* 2015) (Gill, *et al.* 2016) [10, 21]. Finally, it increases the expression of

genes linked to heat sensitivity, enhancing plant cells resistance to heat stress (Ghaffari, *et al.* 2019) (Hosseini, *et al.* 2018) ^[20, 24]. Furthermore, in the absence of extensive validation in field settings, the majority of current research concentrates on small-scale experiments conducted in laboratories. Additional research is still needed to determine the precise chemical pathways and physiological processes by which *P. indica* influences plant heat tolerance. Future studies should thus focus on the impact of *P. indica* on various crop species, growth stages, and environmental conditions in addition to exploring the precise molecular and physiological pathways by which it improves plant heat tolerance. More efficient biotechnology approaches to improve crop response to ever more intense high-temperature stress may result from this. Three theories are put out in light of early findings and literature reviews:

(1) By increasing the activity of enzymes linked to chlorophyll synthesis and optimising cellular membrane permeability, *P. indica* may improve plant stress tolerance. (2) *P. indica* may be a major mechanism for enhancing plant resistance to heat and drought by activating important antioxidant enzymes like peroxidase (POD) and superoxide dismutase (SOD). (3) In addition, *P. indica* may influence the production of reactive oxygen species and control the effectiveness of light energy conversion in photosystem II (PSII), which would further modify plant resistance to high temperatures.

7 Role in Biotic Stress Management

Since plants are sessile by nature, they are constantly exposed to environmental cues throughout their lives, which has led to their evolutionary adaptability to various biotic and abiotic environmental restrictions. Effective infections can infiltrate and impact plant health or even result in plant death despite adaptations that are genetically and evolutionarily developed. Like AM fungi, *P. indica* colonises the roots of a wide range of plant species, causing resistance against numerous soil-borne and root diseases as well as systemic resistance to various foliar infections (Johnson, Alex and Oelmüller 2014) ^[28]. *Piriformospora indica* helps plants cope with biotic stress by forming a symbiotic relationship that strengthens defences and shields them against diseases like viruses and fungi (Kumar, *et al.* 2009) ^[30]. Through a number of methods, including as boosting host plant defence, modifying gene expression, and encouraging the synthesis of proline and other defensive chemicals, it does this. Indirectly, the fungus helps plants manage stress by improving their resistance and overall health.

7.1 Induced systemic resistance (ISR) and priming effects

Data supported earlier reports that *P. indica* can shield barley roots from *F. culmorum*-induced antioxidant enzyme depletion. The studies by (Schäfer, *et al.* 2009) and (Jacobs, *et al.* 2011) ^[26, 45] also made it clear that *P. indica* uses MAMPs to trigger immunological reactions, such as oxidative bursts and the activation of genes linked to defence. Accordingly, it makes sense that the increased H₂O₂ content and greater antioxidant enzyme activity in plants pre-colonized by *P. indica* act as a signal to trigger plants' immune system, thereby boosting plants' resistance to pathogens. However, compared to pathogens, endophytes are thought to produce fewer lytic enzymes, preventing the plant immune system from being activated. Additionally, gene products from mycorrhizal fungi are thought to mimic host cell signalling, serving as decoys to get past plant defences and enter plant tissues (Trivedi, *et al.* 2020) ^[55]. In order to engage in the plant immune response, *P. indica* clearly functions in many ways. In general, there is still much to learn

about the intricate relationship between plants and their endophytic bacteria.

7.2 Enhanced expression of defense-related genes (PR proteins, chitinases)

Various defence mechanisms have been developed by plants to defend themselves against pathogen attacks. Both constitutive, pre-existing, and induced, post-exposure defences are included in this category. Several regulatory mechanisms that precisely control the activation of pathogen-specific defence responses are present in plants for efficient defence against pathogen attack (Pieterse and Dicke 2007) ^[37]. There are two stages of plant defence against diseases. In the first, defence responses are triggered by the recognition of pathogen associated molecular patterns (PAMPs) on the pathogen surface. At the second level, defence mechanisms like the hypersensitive response (HR) are triggered by effector molecules that are encoded by the pathogen and released intracellularly in the plant following infection. This causes the infected host cell to undergo apoptosis (Jones and Dangl 2006) ^[29]. In both situations, intricate signalling networks controlling a wide range of cellular reactions govern these quickly triggered defence responses. The synthesis of reactive oxygen species, the generation of antimicrobial secondary metabolites, the lignification of host cell walls, and the transcriptional activation of numerous genes, including those encoding different transcription factors, pathogenesis-related proteins, and secondary metabolism enzymes, all work together to enhance defence responses. (Schäfer, *et al.* 2009) ^[45]. According to earlier research, *P. indica* colonisation lessened the severity of *Alternaria solani*-caused tomato early blight. Additionally, it was noted that certain defense-related genes were up-regulated (Roylawar, Panda and Kamble 2015) ^[44]. Research examined *P. indica*-primed defence responses by identifying genes that differed in expression in tomato plants pre-colonized with *P. indica* and then challenged with *A. solani*. This was done in order to better understand the mechanistic basis of *P. indica*-induced resistance (P-IR) in tomatoes against *A. solani*. cDNA-AFLP and quantitative real-time polymerase chain reaction (qRT-PCR) were used to quantify gene expression (Panda, *et al.* 2019) ^[35]. The transcriptome in tissue challenged by the necrotrophic foliar pathogen *A. solani* underwent a systemic, dynamic reprogramming as a result of *P. indica* colonisation in tomato plant roots, according to the data. In summary, a complex gene network was primed by *P. indica* pre-colonization, which increased resistance to *A. solani*. In order to increase crop plants' horizontal resistance to a wide range of diseases, *P. indica* pre-colonization presents a viable strategy (Panda, *et al.* 2019) ^[35].

7.3 Protection against fungal, bacterial, and nematode pathogens

P. indica initially demonstrated biotic stress protection in barley roots against *Fusarium culmorum* and in shoots against *Blumeria graminis* (Waller, *et al.* 2005) ^[64]. *P. indica* may offer protection against fungal infections to a broad range of plants, as comparable outcomes have been observed in plants belonging to different families. The endophyte may directly prevent root pathogens through antagonistic actions. *P. indica* did not exhibit this type of fungal growth suppression against *F. culmorum* (Waller, *et al.* 2005) or *Pseudocercospora herpotrichoides* (Serfling, *et al.* 2007), although it did so to a lesser degree against *Fusarium oxysporum* (Dolatabad, *et al.* 2012) ^[17, 47, 64]. The systemic induction of resistance by *P. indica* root colonisation is seen, at least for leaf pathogens. It is evident that

systemic colonisation of *P. indica* roots results in resistance, at least for leaf diseases. According to the monocots barley, wheat, and maize, the synthesis of antioxidants and the generation of ROS appear to have a function akin to the previously described abiotic stress defence (Waller, *et al.* 2005) (Serfling, *et al.* 2007) (Kumar, *et al.* 2009) [30, 47, 64]. Compared to control plants, a subset of defense-related genes is earlier and more powerfully triggered by leaf pathogens in barley plants colonised by root endophytes (Molitor, *et al.* 2011) [34]. According to the results of a recent experiment, plants with Root Knot Nematode + *P. indica* produced a comparatively higher yield than plants infected with Root Knot Nematode. This suggests that either *P. indica* directly affects the viability and productivity of Root Knot Nematodes or that *P. indica* even increases plant resistance against the infestation (Atia, *et al.* 2020) [5]. Therefore, the processes behind *P. indica*-induced resistance appear to be comparable to the well-characterized induced systemic resistance reported for plants colonised by rhizobacteria that promote plant growth (Van Wees, Van der Ent and Pieterse 2008) [58].

8. Agricultural and Biotechnological Applications

Numerous biotic and abiotic stressors frequently affect agricultural crops grown in open fields. It has been shown that plant breeders have contributed to the development of stress-tolerant cultivars. Additionally, the knowledge of how genes and proteins change under stress has been investigated by molecular biologists in parallel. Over the past twenty years, there has been a lot of interest in the transgenic approach to stress tolerance (Gill, *et al.* 2016) [21]. *P. indica* is useful for crop tolerance to a variety of biotic and abiotic stresses, according to a number of reports gathered over the past few decades (Franken 2012) [19]. *P. indica* stabilises growth (Gill, Gill, *et al.* 2016) [21] and nutrition in the face of heat, drought, and salinity while lessening the negative effects of stress on the host plants' photosynthetic efficiency (Ghaffari, *et al.* 2019) (Rajput, *et al.* 2022) [2, 20]. A wide range of microorganisms, including *Chlamydomonas reinhardtii*, *Gaeumannomyces graminis*, *Azotobacter chroococcum*, *Pseudomonas fluorescens* (rhizobacteria), *Sebacina vermifera*, and other soil fungi (such as *Aspergillus niger*, *A. sydowii*, and *Rhizopus stolonifer*), interact with *P. indica* (Ansari, Gill and Tuteja 2014) (Bhuyan, *et al.* 2015) [3, 10, 21]. Several studies have shown that *P. indica* colonisation of the host plant's root system can boost the growth and development of the above-ground plant components in addition to encouraging rooting. *P. indica* inoculation has been shown to boost biomass accumulations of herbaceous crops including tomatoes (Aruna, *et al.* 2023) [4], sweet potatoes (Li, *et al.* 2021) [32], and bananas as well as several woody plants like *Feronia limonia* (vyas, Nagori and Purohit 2008), *Azadirachta indica* (Bagde, Prasad and Verma 2010), and trifoliate orange (Yang, *et al.* 2021) [7, 63, 68] in horticultural crops.

Within plant cells, *P. indica* controls calcium efflux and phosphorus influx through signal exchange at the plant-to-plant interface. These signals from endophytes can either trigger growth and development through phytohormones or start planned cell death (Pérez-Alonso, *et al.* 2020) [36]. Plants with mutations that affect the metabolism of gibberellic acid (GA) and jasmonic acid (JA) show reduced colonisation and growth inhibition (Pinski, *et al.* 2019) [38]. *P. indica* colonisation causes DNA breakage and cell shrinkage, whereas calcium and phytohormones control gene expression during programmed cell death (PCD) (Prasad, Katoch and Shahid 2022) [39]. The development of endoplasmic reticulum (ER) stress and the

regulation of the unfolded protein response (UPR) may be the cause of structural changes in Arabidopsis roots after cell death linked to *P. indica* colonisation (Simoni, *et al.* 2022) [22]. Additionally, *P. indica* colonisation has been associated with higher levels of N, P, and K in black lentils and chickpeas while reducing Fe and Cu deficits in sugarcane (YANG, *et al.* 2020) [67].

8.1 *P. indica* as Phosphorus transporter

Phosphorous is the second most crucial macronutrient for crop development after nitrogen and one of the seventeen nutrients required for plant growth. Due to its high requirement for nucleic acids and its involvement in numerous other activities including photosynthesis and phospholipid functioning, phosphorus can make up as much as 0.5% of the dry weight of plants (Balemi and Negisho 2012) [9]. The axenically cultivable root colonizing endosymbiotic fungus *Piriformospora indica* shares many characteristics with AM fungi. It can colonise the roots of a variety of higher plants, including those that cannot form symbioses with AM fungi, and it encourages the growth, disease resistance, and nutrient uptake of its hosts (Unnikumar, Sree and Varma 2013) (Xu, *et al.* 2017) [56, 65]. These characteristics make it possible to use the fungus as a biocontrol agent, bioregulator, growth and yield stimulant, and biofertilizer, among other applications in the field (Malla, *et al.* 2004) [33]. A study revealed that the fungal P transporter PiPT contributes to the growth of maize by delivering P to the host under conditions where P is deficient (Yadav, *et al.* 2010) [66]. Although it has been suggested that the process may take place at the plant-fungus interface, the exact mechanism of this phosphate transfer from the fungus to the plant is yet unknown. Phosphate efflux from the fungus is made possible by the first transporter, and the plant's uptake of phosphate is mediated by the second (Rausch and Bucher 2002) [43]. According to a report (Shahollari, Varma and Oelmüller 2005) [48], *P. indica* increases the phosphate uptake in Arabidopsis seedling sand by two to three times. This suggests that *P. indica* promotes Arabidopsis growth in a manner similar to that of mycorrhizal fungi. Yadav, *et al.* 2010 [66] revealed that *P. indica* plays a role in the transfer of phosphate to the host Zea mays plant, and suggested that PiPT's involvement in indirect phosphate transport to host plants provides insight into the molecular mechanism behind *P. indica*-mediated phosphate transport to the host plant.

8.2 Plant Stress Response Mediator and Bio-control Agent: *P. indica*

The colonisation of *P. indica* is thought to activate the antioxidant system, improving crop plants' resistance to both biotic and abiotic stressors (Prasad, *et al.* 2013) [40]. *P. indica* has demonstrated its ability to provide bio-protection against *B. graminis* f. sp. tritici, *P. herpotrichoides*, and *Fusarium culmorum* (Serfling, *et al.* 2007) in *T. aestivum*, as well as against the root parasite *Fusarium verticillioides* in *Z. mays* (Kumar, *et al.* 2009) [30, 47]. Compared to non-colonized plants, the fungus-colonized plants were less vulnerable to *Alternaria alternative* and *Colletotrichum falcu* (Verma, *et al.* 2012). Additionally, mycorrhizal fungi are crucial for supplying the root cells with either ammonium or nitrate. Amino acids are thought to be the main substances that help transmit nitrogen to the host plant, and mycorrhizal fungi are thought to preferentially attract ammonium from the soil over nitrate (Guescini, *et al.* 2003) (Sherameti, Tripathi, *et al.* 2008) [22, 51]. There have been reports of *P. indica* producing hydroxamic acids, a secondary metabolite that acts as a natural insecticide (A. Verma, *et al.* 1999) [60]. Recent research has shown that *P. indica*

offers economically significant horticultural and agricultural crops enormous bioprotective capabilities against a variety of plant diseases and insect pest attacks (Verma, *et al.* 2012). Although *P. indica*-infested crop plants have been shown to show additional resistance against pathogenic fungi, the fungus

could be used to boost fungal disease resistance in plants (Waller, *et al.* 2005) [64]. Here it is a table which contains some research work related to the bio control activity of *P. indica* (Table. 1)

Table 1: Plant infections and their corresponding illnesses are controlled by *Piriformospora indica* colonising roots

Pathogen	Disease/Symptom	Host	Reference
Blumeria graminis f.sp. graminis	Powdery mildew	Barley	(Waller, <i>et al.</i> 2005) [64]
Blumeria graminis f.sp. tritici	Powdery mildew	Wheat	(Serfling, <i>et al.</i> 2007) [47]
Cochliobolus sativus	Root rot	Barley	(Waller, <i>et al.</i> 2005) [64]
Fusarium culmorum	Fusarium root rot	Barley, wheat	(Waller, <i>et al.</i> 2005)(Serfling, <i>et al.</i> 2007) [47, 64]
Fusarium verticillioides	Maize root disease	Maize	(Kumar, <i>et al.</i> 2009) [30]
Pepino mosaic virus	Yellow leaf mosaic	Tomato	(Fakhro, <i>et al.</i> 2010) [18]
Pseudocercospora heliothridae	Eyespot	Wheat	(Serfling, <i>et al.</i> 2007) [47]
Verticillium dahlia	Verticillium wilt	Tomato	(Fakhro, <i>et al.</i> 2010) [18]
Pepino mosaic virus	Yellow leaf mosaic	Tomato	(Fakhro, <i>et al.</i> 2010) [18]
Rhizoctonia solani	Rhizoctonia root rot	Barley	(QIANG, <i>et al.</i> 2011) [41]
Heterodera schachtii	Cyst nematode	Arabidopsis	(Daneskhah, <i>et al.</i> 2013) [14]
Alternaria brassicae	Leaf blight	Arabidopsis	(verma, kost and Oelmüller 2013) [61]
Verticillium dahlia	Verticillium wilt	Arabidopsis	(Sun, <i>et al.</i> 2014) [54]

9. Interaction with medicinal plants

The existence of several complex compounds with varying compositions, referred to as secondary plant metabolites, gives medicinal plants their therapeutic qualities. Aromatic plants give many of the various cures that the plant kingdom has to offer to humanity. AMF has a well-established positive effect on *C. forskohlii* (Boby and Bagyaraj 2003) [11]. It's interesting to note that *P. indica* significantly accelerated and boosted *C. forskohlii* flowering (Das, *et al.* 2011) [15]. Aerial growth and biomass production increased when *P. indica* was present during the growth of *C. forskohlii*. When compared to the non-colonized plants, the *P. indica*-colonized six-month-old plants showed a substantial increase in height, number of branches, average branch length, number of leaves, and leaf area (Das, *et al.* 2011) [15]. According to a study, when the medicinal plants *Withaniasomnifera* and *Spilanthes calva* were inoculated with the root endophyte *Piriformospora indica* in nurseries and then moved into the field, both plant species growth and yield significantly increased in comparison to uninoculated controls (Rai, *et al.* 2001) [42]. Another study showed that Chlorophyll content and plant biomass increased overall as a result of the interaction between *A. vera* and *P. indica* (Sharma, *et al.* 2014) [49]. In both *in vitro* and *ex vitro* settings, *P. indica*-colonized *A. vera* plantlets showed improved growth in terms of increased shoot and root length, number of shoots, and number of roots.

10. Future prospects of *P. indica*

Recent research has shown that *P. indica* has multiple uses in improving plant performance. It has been repeatedly demonstrated that the most frequent effects are the induction of resistance against infections and the promotion of vegetative growth. *P. indica* colonisation has beneficial impacts on plant resilience and vegetative growth, but it can also increase crop production and product quality (Waller, *et al.* 2005) [64]. The ability of this fungus to be grown on various medium without a host (S. Verma, *et al.* 1998) and produce substantial amounts of fungal biomass has prompted researchers to suggest its use in next plant production systems (A. Verma, *et al.* 1999) (Franken 2012) [19, 62, 60]. The processes by which *P. indica* promotes plant growth are still up for debate, especially whether the fungus contributes in any way to plant P uptake as observed in the AM symbiosis. On the positive side, *P. indica* and its Sebacinale

relatives have a lot of potential as plant strengtheners and biopesticides. The introduction of sebacinale and fungi into crop production may therefore require special efforts to define the molecular and biochemical bases of sebacinale and symbioses and their physiological effects on crop plants. Due to its ease of *in vitro* propagation and accessibility for fundamental physiological and genetic research, *Piriformospora indica* has some potential for practical usage. The creation of a *P. indica* "mimic" molecule enables the effective induction of secondary metabolites and plant biomass growth in plants that are significant for both medicine and the economy. High biological potential chemicals, which may act through a variety of receptors, can be provided in regular growth media at typical growth temperatures and light levels. Further research is also required to determine the growth-promoting component of *P. indica* that can be effectively employed as a plant bio stimulant. Moreover, the benefits for the host are similar to those of AMF, despite the fact that they arise from a single fungus-host interaction, and it is likely to have an even greater host range than individual AM species. It has previously been demonstrated that when *P. indica* is cultivated in pot cultures, it benefits colonised host plants in a number of ways.

11. Conclusion

Many crop plants, as well as around 80% of all terrestrial plants living in their natural environments, associate with AMF, which is widely known for offering a variety of advantages to its hosts. AMF's technical use in agriculture has mostly been limited to organic farming practices. The use of biocides and fertilisers, tillage, and monocropping, however, reduces the diversity of AMF and limits its potential advantages. *P. indica* is a remarkable endophyte that has been promoted as a potential biofertilizer and biocontrol agent due to its capacity to colonise and benefit a wide range of unrelated host plants. Finding the *P. indica* active ingredient that produces the stimulatory effects is crucial for working in harmony with nature. Future research that isolates and characterises a bio stimulant from *P. indica* will aid in the improvement of agriculture because *P. indica* has been shown to have effective biocontrol and biofertilizer effects.

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