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Fungal Endophytes: A Potent Microbiome for Plant Growth Promotion

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Abstract

Endophytes encompass a diverse array of microorganisms including bacteria, fungi, archea and protists inhabiting the internal tissues of host plants with a particular focus on bacteria and fungi as the extensively researched groups. These endophytes harbor plant growth promoting (PGP) characters like nitrogen fixation, phosphate solubilization and production of phytohormones, siderophore, hydrogen cyanide and ammonia. Of these endosymbiotic group of microorganisms, Plant Growth Promoting Endophytic Fungi (PGPEF) are considered pivotal owing to their reproducibility. The effectiveness of the bioinoculants hinges on the specific criteria set for these endophytes, and it is equally crucial to rigorously assess their performance in field conditions. Adequate knowledge on phytocompounds produced by fungal endophytes and understanding their mechanism in promoting growth of the plants in which they are applied as bioinoculants is inevitable to design a formulation for sustainable agriculture. This review focusses on the comprehensive analysis of essential criteria required to select promising fungal endophytes for application at the field level. The effective utilization of endophytes can be facilitated by the amalgamation of diverse growth-enhancing attributes alongside the capacity of colonization and establishment within the host plant.

***Key words*:** Endophyte, PGPEF, Stress tolerance, Growth promotion

The term “endophytes” originally postulated by De Bary in 1886 was derived from the Greek word where ‘*endon’* refers to ‘within’ and ‘*phyton’* refers to ‘plant’ and these are microorganisms residing in the inner parts of the plant without causing any apparent damage to the host plant [1-3]. Generally, microorganisms are less explored as endophytes because they are colonized on the internal tissues of the plant parts for a particular period of the life cycle or they may be localized on the plant part [4]. The first described seed fungal endophyte was *Lolium temulentum* [5]. Endophytic colonization varies to a great extent where the mode of colonization of microorganisms with the host plant is achieved either from the root to shoot or shoot to flower or from the flowers to seeds and sometimes via wounds and injury [6]. They are vertically transmitted from one generation to another through seeds and they offer several beneficial effects such as growth promotion to the host plants [7], protection from pest attacks [8], prevention of biotic and abiotic stress in plants [9-10], and increased nutrient uptake for the growth of the crop plants [11]. Endophytes thrive in environments that foster enhanced interactions with their host employed [12]. Presence of beneficial endophytic microorganisms in the host plants assists them in prevailing over adverse environmental conditions and prove to suppress diseases and infections caused by phytopathogens and nematode attacks [13]. Endophytic fungi are numerous in single host species and screening for potent endophytic mycofloras and implementing them as consortium will contribute to improvise crop performance compared to the usage of one particular endophytic strain. Some of the notable endophytic fungi employed as bioinoculants are *Fusarium* sp., *Aspergillus* sp., *Trichoderma* sp., *Penicillium* sp., and *Colletotrichum* sp. etc. [14]. The ongoing demand for identification of such novel strains of endophytic fungi and their characterization persists due to the imperative of promoting environmental sustainability. Moreover, these microorganisms have remained relatively underexplored and warrant greater attention and promotion within the scientific community to unlock their full potential. This review will furnish comprehensive insights for the selection of promising fungal endophytes to explore in the realm of crop enhancement and these favourable attributes of potential endophytes make them valuable for promoting growth and protection of crop plants.

Classification of endophytic fungi

Fungal Endophytes are classified generally into four classes (Fig 1) based on the traits such as host colonization, transmission patterns and symbiotic association. Clavicipitaceous endophytes (Class 1) are specific colonizers in grass on the shoot and rhizome of the host plant portion that are transmitted vertically and horizontally. They confer non-habitat adapted fitness to the growth of the plants. Non-Clavicipitaceous endophytes (Class 2) are not found in grass but transmitted vertically and horizontally, colonize root, stem and leaves and in addition confers non-habitat adapted and habit adapted fitness. Class 3 endophytes are associated on the leaves of tropical trees, transmitted horizontally and are non-habitat adapted and Class 4 endophytes are sterile forms having dark septate mycelium (DSE) that produces melanin. They are localized on the roots and get transmitted horizontally with non-habitat adapted resulting in growth promotion irrespective of the place of origin. All the four classes exhibit mutualism in association [15].

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Class 1 Clavicipitaceous endophyte	Associated with grass Vertical and horizontal transmission Colonizes the aerial part / root
Class 2 Non- Clavicipitaceous endophyte	Not Associated with grass Vertical and horizontal transmission Colonizes the root, stem and leaves
Class 3 Endophytes	Associated with leaves of tropical trees Horizontal transmission Colonizes the Shoot
Class 4 Dark septate mycelium endophytes	Associated with terrestrial plant roots Horizontal transmission Colonizes the Roo

Fig 1 Criteria to characterize fungal endophytic class

Endophytic fungi: Plant- microbe interaction

Endophytes vary greatly in single host species with their endophytic community based on the climatic conditions, seasons, geographic continuity and are localized in a part of the plant [16-17]. Endophytes help in combating several abiotic stress conditions, which include adverse climatic conditions with low/high temperature, drought conditions, high/low saline conditions and toxic heavy metals [18-19]. They also help in combating biotic stresses that occur in crop plants such as infections caused by phytopathogens, insects, herbivores and nematodes. Moreover, these endophytes influence the developmental and behavioural pattern of the host plant via hyphal development and genes encoding for sporulation further promoting colonization and establishment of endophytic niche [20-21]. Colonization of endophytic fungal strains in the host plant will contribute to a sustainable agriculture by suppressing the negative impact on the plant physiology and plant development by inducing resistance against stress conditions and production of secondary metabolites [22]. Endophytic colonization often offers fitness and health benefits to the crop plants when compared with uninoculated plants [23]. When these endophytes are interacting with the host plants from the two regions of a locality like native and range expander, their growth pattern is greatly influenced by the plant-endophytic interactions depending on the plant growth stages. In a study by Geisen *et al.* [24] experiments conducted on six commonly growing herbaceous plants from Netherlands were used for the experiments which revealed that the interactions of the host and endophyte remains unique from seedling germination to different growth stages. Fungal endophytes promoted the growth of the plant in range expanders than on native plants and this pattern may vary based on the endophytic interactions. These endophytes support the plant growth directly and indirectly in several ways by nutritional acquisition, production of phytohormones, secondary metabolites that aid in protection of host from biotic and abiotic stresses [22].

Endophytes are capable of producing several secondary metabolites and bioactive compounds. Such a trait will protect the plant from pest and pathogenic attack through the secretion of certain amino acids of bad taste or odour as well as help in promotion of induced resistance thus causing set back of pathogens from invading the host plant. Production level of the secondary metabolite varies based on the season of sample collection, climatic condition and geographical locations [25]. In a fresh medium secondary metabolite production will be higher in the static phase and then decreases as the medium gets aged up as there will be depletion in the nutrient level present in them [26]. Production of these bioactive compounds is effective when the host and the endophyte are in association and when the culture parameters are maintained for their ideal growth conditions [27]. Bioactive compounds obtained from an endophytic fungus *Aspergillus terreus* revealed antifungal activity with the zone of inhibition of about 3.0 -8.3 mm against *Trichophyton mentagrophytes* and *T. rubrum*. *Aspergillus* sp. contain antibiotics exhibited antimicrobial activity [28]. These secondary metabolites from endophytes will be a pivotal source of novel antimicrobial compounds that may help in both agricultural and industrial sectors.

Characteristics of plant growth promoting endophytic fungi

Fungal endophytic strains interact with their respective hosts and are capable of releasing phytohormones, siderophores and other volatile organic compounds which may directly or indirectly influence the growth of the crop plants (Fig 2, Table 1) [29-34].

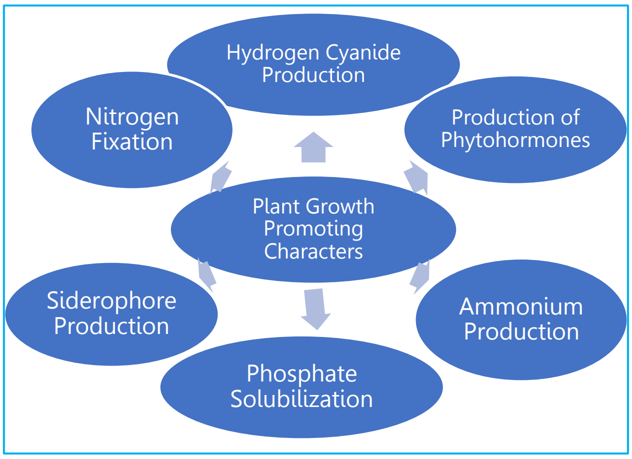

Fig 2 Traits of endophytic fungi

Production of phytohormones

Indole Acetic Acid is a well-established plant hormone that is known to have positive effect on the plant growth and development. IAA is well known to improve the growth of the plant by increasing the production of primary and lateral roots [35] that results in better absorption of nutrients and increase in biomass leading to shoot development and yield enhancement [36]. Moreover, IAA produced by these endophytic strains act as a first line of defense against several phytopathogenic attacks by activating induced systemic resistance [37]. Endophytic fungal spores of *Trichoderma virens* and *T. atroviride* from rhizosphere when tested on *Arabidopsis* sp. for plant diffusing properties resulted in the increased rooting and shooting thereby producing a positive impact on the plant biomass [36]. Similar results were observed when the endophytic strain *Fusarium* sp. was inoculated on *Euphorbia pekinensis* [38]. In microorganisms, tryptophan acts as a precursor for the production of IAA. Some endophytic strains produce IAA naturally and others produce IAA with the supplementation of tryptophan. In one such study endophytic extracts of six different fungal strains increased the root length of *Arabidopsis thaliana* with the application of tryptophan [39].

Endophytic strains *Aspergillus fumigatus* TS 1 and *Fusarium proliferatum* BRL1 isolated from the roots of *Oxalis corniculata* had the potential of producing IAA and they were quantified using GC/MS – SIM from their culture filtrates [40]. However, BRL1 produced higher quantity of IAA (0.861 ± 0.026 mg/g) as compared to TS1 (0.353 ± 0.0027 mg/g).

Gibberellins are phytohormones utilized for the growth promotion in plants for stem elongation. Furthermore, Gibberellic acid (GA) produced by several endophytic fungal strains protects the plant from adverse environmental conditions and biotic stress [41]. In a study conducted by Hamayun *et al.* [42], endophytic fungus *Porostereum spadiceum* AGH786 was found capable of producing gibberellins that promoted the growth of soya bean when compared with plants without fungus. In addition, the treatment resulted in overcoming salt stress in these plants. Roots of *Oxalis corniculata* screened with two endophytic fungal strains namely *Aspergillus fumigatus* TS1 and *Fusarium proliferatum* BRL1 were capable of producing both physiologically active and inactive GA which had positive impact on the growth of mutant rice Waito - C plants [40]. GA producing endophytic strains namely *Aspergillus* sp. and *Penicillium* sp. from *Monochoria vaginalis* promoted growth in Waito – C [43]. *Penicillium citrinum* (KACC43900) endophyte from the roots of *Ixeris repenes* secretes GA higher than the wild type of *Gibberella fujikuroi* in a study conducted against mutant rice and *Atriplex gemelinii* seedlings [44]. Production of phytohormones increased the above ground photosynthetic processes and germination percentage that resulted in increased production in the performance of *Zea mays* [45].

Endophytic strains potential of producing growth hormones such as IAA, GA, are also capable of parasitizing pathogenic fungi and nematodes in crop plants such as in wheat [46], tomato [47], sorghum [48] and *Phaseolus vulgaris* [49]. These fungal endophytes not only increased the seed vigour and biomass but also decreased abscisic acid and jasmonic acid hormone accumulation. In a study conducted by Ismaila *et al.* [50], twenty-nine fungal endophytes isolated from the leaves of *Citrullus colocynthes* L. (bitter apple/colocynth) were witnessed with the production of phytohormones (IAA and GA). When these fungal culture filtrates were tested on rice plants majority of the strains promoted the growth of rice seedlings.

Ammonia production

Ammonia production by the endophytic strains is considered to be an essential trait in promotion of crop plants. Endophytic fungi assimilate ammonium from the environment and convert them to different nitrogen containing compounds such as glutamine and asparagine. Endophytic fungus associate with ammonium-based metabolism for their nitrification and denitrification process which supports the plant's health and nutrient cycle. Ammonium production varies based on the endophytic strains which help in promoting root and shoot elongation in crop plants by accumulating nitrogen in the plant through nitrification [51]. *Agaricus bisporus* and *Mycoleptodiscus* sp. isolated from *Vanda cristata* had maximum ammonium production which could help in the growth of various cereals and legume crops [52]. Among the 18 isolates from *Ocimum sanctum* and *Aloe vera*, three endophytic isolates proved as best producers of ammonium and aided in nitrogen availability and promoted seed vigour on green gram and paddy [53]. Endophytic strains *Penicillium oxalicum*, *Alternaria alternata, Daldinia sp, Fusarium circinatum, Pestalotipsis versicolor, Penicillium megasporum* isolated from the leaves of *Cupressus torulosa* were capable of ammonia production aids in plant growth promotion and certain strains act as an antagonist against pathogenic fungi [54]. Several endophytes from *Ephedra pachyclada* such as *Penicillium caseifulvum, Alternaria tenuissima, Aspergillus flavus, Penicillium commune, P. crustosum* produced ammonia. When used as bioinoculants on maize plants these strains resulted in a significant increase in the growth of crop plants [55]. In a similar study by Hassan [56], fungal endophytes *Penicillium chrysogenum* and *P. crustosum* from the medicinal plant *Teucrium polium* L. produced ammonia and IAA which supports the growth of the maize plants by increasing the biomass. Ammonia produced by the fungal endophytic strains regulates metabolism required for entire plant life cycle and also proved to enhance the growth of the host plants [52].

Phosphate solubilization

Solubilization and mineralization of inorganic phosphates to organic forms by endophytes makes them available to the plants to have a positive impact on soil quality. This enables them to be promoted as successful candidates for use as biofertilizers and biocontrol agents [57]. Inoculation of endophytic fungal strains like *Aspergillus niger, Gliocladium virens and Rhizopus oligosporus* on *Zea mays* had reduced commercial nitrogen and phosphorus fertilizer intake up to 50% and promoted the growth of the plant [58]. Endophytic aquatic fungus, *Tetracladium setigerum* Grove (Ingold) isolated from healthy roots of *Berberris vulgaris* were used as a biofertilizer owing to its phosphate solubilization activity. This feature helped in plant growth promotion and protection against pathogen attacks [59-61]. *Taxus wallichiana* roots had the endophytic strains namely *Aspergillus versicolor* and *Penicillium daleae* which had phosphate solubilization activity in the presence of calcium, iron and aluminium as per the study conducted by Adhikari and Pandey [62]. *Curvularia geniculata* obtained as endophyte from *Parthenium hysterophorus* when inoculated into *Cajanus cajan* resulted in phosphate solubilization, phytohormone production which had better growth of the plants compared with that of uninoculated control plants [63].

Siderophore production

Siderophore is a greek word, "sidero" refers to "iron" and "phore" refers to "carriers" hence they are iron carriers [64]. These siderophores are iron chelating compounds with low molecular weight produced by the microorganisms under iron starved conditions. They form complexes with other elements like Mo, Mn, Co, and Ni. Based on the functional group siderophores are termed either as hydroxamate type or carboxylate type. Most of the fungus produce hydroxamate siderophores with the basic structural unit N^{δ} - acyl - N^{δ} - hydroxyornithine [65] but few zygomycetes produce polycarboxylate siderophore rhizoferrin containing two citric acid residues linked with 1,4 butanediamine [66]. Depleted iron concentration initiates the production of siderophores in such endophytic fungi [67]. *Acremonium* sp. a fungal endophyte isolated from the bulbs of *Lilium davidii* in a study on seedling germination of *Allium tuberosum* resulted in plant growth promotion by the production of siderophore [68]. NGB-WFE16 (*Fusarium petersiae*) endophyte isolated from a wild medicinal plant *Cheilanthes vellea* were capable of producing siderophore that resulted in an antagonistic effect against the phytopathogen *Alternaria alternata* [69]. In a study by Kulišová *et al.* [70], siderophore production was found in the endophyte isolated from berries and leaves of *Vitis vinifera*. Recombinant *Trichoderma harzianum* strains (T_{13} and T_{15}) were found positive for the production of siderophores in a study conducted by Eslahi *et al.* [71]. Such endophytic strains can be utilized as potential bioinoculants for the plant growth promotion in iron deprived soil conditions.

Nitrogen fixation

Nitrogen is considered as one of the most important macronutrients utilized by the plants for the growth and development. Nitrogen freely available in the atmospheric air is converted to usable forms by the association of microorganisms with their respectable host plant which assist in the growth of the crop plants by significant increase in nodulation and nitrogen fixation [72]. According to the study by Xie *et al.* [73], endophytic fungus *Phomopsis liquidambaris* was isolated from the inner bark of the stem of *Bischofia polycarpa* promoted the yield enhancement and increased nodulation and nitrogen fixing abilities in peanut plants. *Colletotrichum tropicale* fungal endophyte from *Theobroma cacao* increased nitrogen uptake and biomass in *Theobroma cacao* plants [74]. *Colletotrichum* sp isolated from different parts of *Plumbago zeylanica* was found to have almost all the plant growth promoting characters [30]. Root endophytic fungus *Piriformospora* sp colonized root cortex of maize plants and promoted the growth of the plants [75]. *Phoma* sp. an endophytic strain isolated from the leaves and stem of *Tinospora cordifolia* and *Calotropis procera* when inoculated in the maize seeds influenced the biomass by increasing the fresh and dry weight compared to untreated controls. Proliferation of root hairs in treated plants helped in better anchorage and nutrient absorption [45].

Hydrogen cyanide production (HCN)

Hydrogen Cyanide (HCN) is a volatile compound offering indirect effects on the growth promotion. *Cladosporium cladosporioides* and *Fusarium equiseti* isolated as endophytes from wheat plants had the ability for HCN production and ammonia that aided in the indirect promotion for the growth of the plants against abiotic stress conditions like drought and temperature [76]. Hence application of these endophytes could be used as biofertilizers for eco-friendly crop management (Fig 3). In a study conducted by Chowdary and Sharma [77], *Chaetomium globosum* and *Trichoderma harzanium* were found as endophytes from the inflorescence of *Aloe vera*. When these endophytes were tested against *Sclerotinia* stem rot disease caused by plant pathogenic fungus *Sclerotinia sclerotiorum*, they exhibited the promising plant growth promoting characters like production of IAA, siderophore and Hydrogen Cyanide which suppressed the weeds and pathogen attacks. The percentage of disease suppression rate varied based on the substrate used by 69% Czapek Dox agar and 55 to 81% potato dextrose agar. *Aspergillus terreus* an efficient fungal endophyte from tomato plant with HCN activity could promote the growth of tomato plants than the uninoculated control plants in vitro conditions [78]. Endophytic fungus *Colletotrichum* sp. from *Plumbago zeylanica* can be used as a biofertilizer on the crop plants and they exhibited promising plant growth promoting characters [30]. Endophytic isolate *Penicillium chrysogenum* T_8 from tomato plants were capable of producing HCN along with IAA (0.11±0.05 µg/mL), siderophore production was maximum at 20th day and phosphate solubilization index was about 2.6 ± 0.3 mm which offered increase in the biomass of the tomato seedlings when compared with the untreated control plants [79].

Volatile organic compounds

Endophytic microorganisms are capable of producing certain volatile organic compounds such as isoprene, monoterpenes, sesquiterpenes and oxygenated compounds that might have contributed to the growth of the plant by defending them against phytopathogens. Volatile compounds have low molecular weight and hence they diffuse better in atmospheric gases [80]. In a study conducted by Hassan *et al.* [81], *Nodulisporium* sp. an endophyte from *Thelypteris angustifolia* is capable of producing several forms of ketone and used as biological control for plant disease. Horseradish (*Armoracia rusticana*) contains 43 endophytes with several sensitive VOC's like methylformate, methylacetate, ethylacetate, dimethyl sulfide which seemed different on different isolates [82]. Some fungal VOC's are semiochemicals that act as signalling molecules [83]. β- caryophyllene terpenoid a volatile compound emitted from *Talaromyces wortmannii* owns plant growth promoting fungal traits by inducing resistance [84]. Novel endophytic fungus *Muscodor albus* produced volatile gas that suppressed smut of barley when the seeds were infested by *Ustilago hordei* [85].

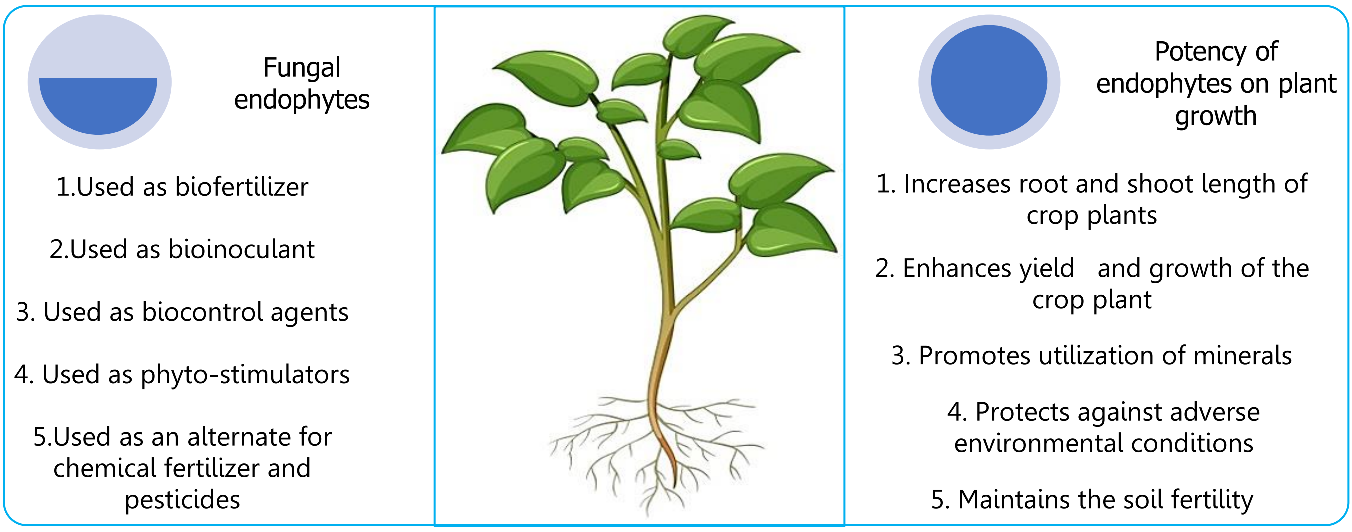

Fig 3 Application of fungal endophytes

Endophytes as bioinoculants

Endophytic fungal strains like *Neocosmospora solani* formerly known as *Fusarium solani* with their capability of secreting bioactive compounds when artificially introduced into host system, serve as a source against microbes and insects by unleashing the secondary metabolites thereby enhancing defense mechanism and preventing against deterioration of crop loss [86-87]. In a study by Mastan *et al.* [88], growth of *Coleus forskohii* is greatly influenced by the application of wheat bran based endophytic formulations of three fungal strains viz., *Fusarium redolens, Phialemoniopsis cornearis, Macrophomina pseudophaseolina.* Bio active compounds from different endophytic fungal strains influences several ecological roles in plant health by serving as the excellent source of antimicrobial activity against gram positive and gram-negative bacterial strains. *Alternaria alternata* isolated from the leaves of *Azadirachta indica* owns antibacterial activity against *Bacillus subtilis* and *E. coli* [89]. Endophytic strain *Cladosporium oxysporum* isolated from *Euphorbia bupleuroides* when used as biocontrol against the black bean aphid (*Aphis fabae*) resulted in the reduction of disease suppression when culture filtrates were used as invert emulsions and aqueous cultural filtrates. This study is evident that the invert emulsion performed better than the aqueous culture filtrates in controlling the aphids when used as bioformulations [90]. Significant potential of the compounds were analyzed using thin layer chromatography and GC-MS studies. Such influential strains when introduced into the fields overcome adverse environmental conditions like drought and salt stress [91]. When these two promising endophytic fungal strains namely *Penicillium* sp. and *P. glomerata* were tested upon cucumber plants under saline and drought conditions, they modulated the growth in terms of biomass and increased the height of the plant in treated plants than the untreated control [92]. The best way to choose endophytic microbes for growth promotion and protection relies on comprehensive understanding related to disease mechanism and pathogenesis of a pathogen. Ensuring to learn the different pathways of pathogenesis and techniques to produce bioformulations will support the growth of the crop plants and ward off the host plant against pathogens and influences the world of agriculture by exploring plants with diverse secondary metabolites which could be used in the field of agriculture. By doing so crop plants produced shall own good resistance and nutritional profile to guard the health of human life.

Challenges faced in employing fungal endophytes as bioinoculants

Fungal endophytes have gained significant attention in the recent years as they are plant growth promoting, alleviating stress and reducing the dependency on chemical fertilizers. However, implementation of these strains as bioinoculants at the field level is faced with many challenges and obstacles by researchers and practitioners. These challenges are encountered at different levels, the first level being the selection of strains with wide adaptability across different plant species and environmental conditions. Furthermore, these fungal endophytes exhibit various levels of host specificity that may hinder their performance. Achieving high levels of compatibility between the selected strain and the target plant is indeed a huge challenge that needs to be addressed properly. Ensuring effective plant- microbe interaction and colonization abilities might overcome this drawback.

New methodologies to develop effective formulations and their delivery to the plant system are the prime areas of focus in research with endophytes. Moreover, safety and regulatory measures have to be ensured to prevent the toxicity effects of endophytes on humans and environment. Consistent performance, persistence in host plant by effective colonization, establishing a successful ecological niche with the residing microbial community are the key factors to be considered for promoting endophyte based bioinoculant applications to target various stress posed to crop plants. Large scale production and scale up process of endophytes are currently the prerequisite for employing potential endophytes as biofertilizers.

Application of endophytic fungal strains on the host plant as bioinoculants remains successful in most of the cases as they result in promotion of crop plants growth and yield by preventing against phytopathogens. This is accomplished by the colonization of the endophyte to the host plant. Fungal endophytes when exposed to high temperature and also on application of synthetic or biological fungicides over the seeds for protecting them during transportation to ward off against pathogens might weaken / kill the beneficial microbiome present in or the surface of the seeds. There are certain ways of preserving the fungal endophytes such as maintaining them under low temperature and low humidity and avoiding application of fungicides on seeds as they might kill the beneficiary microbe during germination [93].

CONCLUSION

Despite the challenges, fungal endophytes prove to be a promising resource to harness for growth, development and crop protection as highlighted in this review. Integrating various disciplines to overthrow ecological challenges and hurdles, innovative research and continuous search for new promising strains will pave a way to employ them as potential bioinoculants.

Table 1 List of plant growth promoting fungal endophytes and its mode of action on plants

S. No.	Plant growth promoting character	Name of the endophyte	Crop plants	Functional characteristics	Reference
1.	Indole Acetic Acid	*Trichoderma virens* and *Trichoderma atroviride*	*Arabidopsis*	Increased rooting, shooting and biomass	[36]
		Fusarium spp.	*Euphorbia pekinensis*	Improved the biomass	[38]
		Fusarium sp., *Alternaria* sp. and *Didymella* sp.	*Arabidopsis thaliana*	Increased the root length	[39]
		Fusarium oxysporum	Wheat	Increased the root and shoot length, inhibits the growth of weed *Avena fatua.*	[46]
		Pocnia chlamydosporia	Tomato	Increased the root and shoot length	[47]
		Trichoderma asperellum	Sorghum	Increase the seed vigour and yield	[48]
2.	Gibberellins	*Porostereum spadiceum* AGH786	Soya bean	Growth promotion and alleviation of salt stress	[42]

		Aspergillus fumigatus TS1 and *Fusarium proliferatum* BRL1	Mutant rice Waito - C plants	Growth promotion	[40]
		Aspergillus Sp. and *Penicillium Sp.*	Waito - C plants	Growth promotion	[43]
		Penicillium citrinum (KACC43900)	Mutant rice and *Atriplex gemelinii* seedlings	Growth promotion	[44]
		Phoma sp.	Maize	Increase the germination percentage	[45]
3.	Ammonia production	*Agaricus bisporus* and *Mycoleptodiscus* sp.	cereals and legume crops	Growth promotion	[52]
		Penicillium oxalicum, Pestalotiopsis versicolor and Alternaria alternate	-	-	[54]
		Penicillium caseifulvum, Alternaria tenuissima, Aspergillus flavus, Penicillium commune and *Penicillium crustosum*	Maize	Increase in growth of crop plants	[55]
		Penicillium chrysogenum and *Penicillium crustosum*	Maize	Increased the biomass	[56]
4.	Phosphate solubilization	*Aspergillus niger, Gliocladium virens* and *Rhizopus oligosporus*	*Zea mays*	Reduced the uptake of commercial fertilizers and promoted the growth of the plant	[58]
		Curvularia geniculata	*Cajanus cajan*	Growth promotion	[63]
		Tetracladium setigerum	-	Used as a biofertilizer	[59]
		Aspergillus versicolor and *Penicillium daleae*	-	Soil fertility	[62]
5.	Siderophore production	*Acremonium* sp.	*Allium tuberosum*	Improved seedling germination and plant growth	[68]
		NGB-WFE16 (*Fusarium petersiae*)	Wheat	Antagonistic effect against the phytopathogen *Alternaria alternate*	[69]
		Aspergillus niger, Penicillium crustosum	-	Antifungal activity	[70]
		Trichoderma harzianum strains (T13 and T15)	*Phaseolus vulgaris*	Potential bioinoculants for plant growth promotion and yield enhancement.	[71]
6.	Nitrogen fixation	*Phomopsis liquidambaris*	Peanut	Yield enhancement and increased nodulation and nitrogen fixing abilities	[73]
		Colletotrichum tropicale	*Theobroma cacao*	Increased nitrogen uptake and biomass	[74]
		Colletotrichum sp.	-	Used as a biofertilizer and induce salt stress tolerance	[30]
		Piriformospora spp.	-	Growth promotion	[75]
		Phoma sp.	Maize	Increased biomass particularly profuse root hairs were found	[45]
7.	Hydrogen Cyanide Production (HCN)	*Cladosporium cladosporioides* and *Fusarium equiseti*	-	Abiotic stress tolerance and biofertilizer	[76]
		Chaetomium globosum and *Trichoderma harzanium*	-	Suppressed the weeds and pathogen attacks	[31]
		Aspergillus terreus	Tomato	Growth promotion	[32], [78]
		Colletotrichum sp.	Crop plants	Biofertilizer	[30]
		Penicillium chrysogenum	Tomato	Increase in biomass	[79]
8.	Volatile Organic Compounds	*Nodulisporium* sp.	-	Biological control for plant disease	[81]
		Fusarium sp., *Penicillium* sp. and *Colletotrichum* sp.	-	Antimicrobial effects	[82]
		Muscodor albus	Suppressed smut of barley	disease control	[85]
		Talaromyces wortmannii	*Brassica campestris*	Induced resistance	[84]

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