© 2023, Centre for Advanced Research in Agricultural Sciences
Research Journal of Agricultural Sciences
Volume 14; Issue 05 (Sep-Oct 2023); pp 1393–1397

Open Access
ISSN: 0976-1675 (P)
ISSN: 2249-4538 (E)

Research Review

Endophytic Fungi and Sustainable Agriculture

N. Kistu Singh*[1], M. Shyamkesho Singh[2] and R. R. Pandey[3]

[1-3] Department of Life Sciences (Botany), Manipur University, Canchipur - 795 003, Manipur, India

Abstract

With the increasing world population and urbanization, agricultural lands are diminishing. Prolonged use of chemical fertilizers, pesticides, insecticides, etc. in the fields and antibiotic consumption have led to environmental degradation, reduced soil fertility, increased toxicity, and the development of drug-resistant microorganisms. The agricultural sector suffers huge losses in production due to phytopathogens, insects, water stress, salinity, and temperature. With regard to health and environmental concerns, the development of sustainable agriculture has been a major area of research. The biological control method is a safe and effective approach to controlling plant pathogens and creating sustainable agriculture. Endophytic fungi could protect plants from pathogen attack, improve plant health, and serve as strong biocontrol agents. The application of endophytic fungi in organic farming is important as an input, and it could restore degraded croplands to their natural ecosystem. Endophytic fungi have great potential to resist abiotic stress, which helps plants adapt to various conditions. Along with enzymes and phytohormones, fungal endophytes also produced a number of secondary metabolites with bioactive properties. This review highlights the important roles played by endophytic fungi in the field of agriculture and shows the necessity of conducting further studies and exploring novel endophytic fungi.

***Key words*:** Fertilizers, Phytopathogens, Sustainable, Biological control, Antimicrobial, Phytohormones

Anton de Bary was the first to use the word "endophyte" [1]. The diversity of fungal endophytes varies with the environment, tissue type, and age of the plant [2]. Sun and Guo [3] estimated that there are more than a million endophytic fungi. Endophytic fungi colonize the internal plant tissues of plants in a symbiotic relationship without causing any harmful effects to the host plant and protecting against abiotic as well as biotic stresses [4]. As reported by Petrini *et al*. [5], there are about 1 million endophytic fungi distributed across all ecosystems. In the symbiotic interactions between the endophytic fungi and host plants, the plants provide space and food for the endophytes, and in return, the endophytes help plants with the uptake and utilization of nutrients from the soil. Many endophytic fungi are able to improve the resistance of plants against pathogens, insects, herbivores, drought, salinity, etc. The organic farming practice has gained economic importance in the United States since the 1990s. Organic farming has been defined by the U.S. Department of Agriculture (USDA) as "an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity based on the minimal use of off-farm inputs and on management practices that restore, maintain, and enhance ecological harmony" [6]. In the organic farming system, the use of chemical fertilizers and modified crops have been totally restricted, which conserves soil, water, and energy. Worldwide, organic agriculture is practiced in 187 countries on 72.3 million hectares of agricultural land [7]. Just 2.30 million hectares of the field are being used for organic farming in India, where the practice is still in its infancy [8]. Sustainable agriculture has become a major area of scientific research as it reduces negative effects on the environment as well as protects the soil [9]. The excessive and long-term application of pesticides, insecticides, and fertilizers poses harmful effects on the environment through leaching and human health through the food chain [10]. The excessive use of fertilizers leads to the accumulation of heavy metals, the eutrophication of rivers and lakes, the acidification of soils, the contamination of aquifers and water reservoirs, and the generation of gases associated with the greenhouse effect [11].

Fungicide-resistant plant pathogens have become a major problem in the agriculture sector. The Food and Agriculture Organisation (FAO) has estimated that around 25% of the world's crops are affected by plant diseases each year [12]. There is an increasing need for the development of novel disease management products that can offer environmentally friendly and economically feasible control of crop plant diseases. Biological control mainly relies on the use of antagonistic organisms that broadly or specifically target the pathogen. Antagonistic organisms act on pathogens by various mechanisms, which include mycoparasitism due to physical inter-hyphal interference, competition for nutrients and colonizing space, production of volatile and non-volatile metabolites, or stimulation of host defence [13]. The biocontrol activity using endophytic fungi has been increasing and playing

Received: 22 Apr 2023; Revised accepted: 22 Sep 2023; Published online: 28 Sep 2023

Correspondence to: N. Kistu Singh, Department of Life Sciences (Botany), Manipur University, Canchipur - 795 003, Manipur, India, Tel: +91 9774788842; E-mail: nkistusingh@gmail.com

Citation: Singh NK, Singh MS, Pandey RR**.** 2023. Endophytic fungi and sustainable agriculture**.** *Res. Jr. Agril. Sci*. 14(5): 1393-1397.

an important role in integrated disease management practice. The major drawback of endophytic fungi as a biocontrol agent is their reliability in field conditions due to environmental factors [14]. The market for endophytic fungal inoculants as biological control agents have been increasing worldwide in the last decade [15]. Endophytic entomopathogenic fungi act as insect pathogenic agents by infecting lepidopterous larvae, aphids, thrips, and other cosmopolitan insects, which are of great concern in agriculture worldwide, with little or no risk to non-target organisms or beneficial insects [16]. Bio stimulants and biofertilizers are other applications of endophytic fungi. There has been a report on the utilization of endophytic fungi as nano sensors that can detect pollutants, which might help in bringing a greener environment [17]. The biosynthesis of various metal nanoparticles is a new trend in exploring fungal endophytes for various applications. In this review, the role played by endophytic fungi in bringing sustainable agriculture will be discussed.

Biodiversity of endophytic fungi

Endophytic fungi can be classified based on spore production, mode of transmission, and infection type [18]. The diversity and distribution of endophytic fungi depend on the biotic, abiotic, and maturity of the plant [19]. In research conducted by Zhou *et al*. [20], only a few species of endophytic fungi were found to be dominant and maximum endophytes were uncommon. In the tropics, a single leaf may harbour up to 90 endophytic fungal species, while grassland species can have up to 50 distinct genera [21]. In arctic and boreal environments, endophytic colonization rates range from 1% to 44%, whereas tropical habitats have colonization rates of over 90% [22]. In a recent study, endophytes found in the tropical region showed lower host specificity as compared to endophytes in the temperate region [23]. Ascomycetes, which make up the majority of endophytic fungi, are an ecologically varied group. In the tropical region, plants are found to have a larger number of xylariaceous ascomycetes [24]. The most common classes among ascomycetes were Sordariomycetes, Dothideomycetes, Eurotiomycetes, and Leotiomycetes [25]. Even in polar plants, Ascomycota has been found to be prevalent [26]. Endophytic fungal species have a life cycle that is partially symbiotic and partly saprophytic or latent pathogens, depending on the availability of host tissue or organs [27].

Importance of endophytic fungi in agriculture

The world's population entirely depends on the agriculture sector. The addition of chemicals in the field for increasing production pollutes the environment, leading to the loss of soil properties as well as biodiversity [28]. The ultimate solution to restore soil health is to use a biological approach, especially microorganisms [29]. Due to their distinctive habitat, fungi residing inside plant tissues play an important role in agriculture. The endophytic fungi help the host plant to overcome both biotic and abiotic stresses, promote plant growth by the production of growth hormones, ammonia, and siderophores, and also help in nutrient absorption and assimilation from the soil. The fungal endophytes produce a wide range of secondary metabolites, which increase both the quality and quantity of agricultural crop production. Abiotic stresses such as drought, salinity, extreme temperature, and flood often affect the physiology of plants [30]. Several studies have shown the importance of endophytic fungi in agriculture. Two isolates, *Aspergillus fumigatus* and *Fusarium proliferatum* from *Oxalis corniculata*, have been shown to have siderophores activity, phosphate solubilization, and the production of indole-3-acetic acid [31]. Hamayun *et al*. [32] reported that *Cladosporium sphaerospermum* from *Glycine max* produces a significant amount of gibberellin. The endophytic fungi *Penicillium chrysogenum* and *P. crustosum* isolated from *Teucrium polium* were reported to solubilize phosphate and produce indole-3-acetic acid, and ammonia [33]. In a study, *Trichoderma asperellum* isolated from *Canna indica* L. has been reported to produce 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase, which has lessened the stress of water logging in wheat [34]. Hamayun *et al*. [35] have reported that an endophytic fungus, *Gliocladium cibotii* isolated from *Verbena officinalis*, increases the growth of *Helianthus annuus* and *Glycine max* under thermal stress conditions by producing a ROS-degrading antioxidant enzyme. Several endophytic fungal communities might play a significant role in plant growth promotion and protection, increase productivity, and restore soil health for obtaining sustainable agriculture.

Abiotic stress tolerance

Water scarcity, soil salinization, desertification, deforestation, and urbanization are important problems faced worldwide [36]. The increase in global warming alters rainfall, temperature, O_2/CO_2 ratio, etc., which provoke abiotic stress in plants. The major abiotic stresses include drought, salinity, high heavy metals, UV radiation, and temperature. Abiotic stress brings certain changes to plants, such as morphological, biochemical, physiological, and molecular changes that greatly impact crop productivity [37]. Endophytic fungi improve stress tolerance in plants by certain mechanisms, such as enhancing water uptake, increasing the production of antioxidant enzymes, mainly catalases and peroxidases, and compounds, optimizing metabolic processes, producing phytohormones, etc. [38]. The primary challenge faced by farmers in developing nations every year is drought, which impacts more than 45% of the agricultural area [39]. Chhipa and Deshmukh [40] reported that the endophytic fungus *Penicillium brevicompactum* improves drought resistance in barley plants. Under salinity stress, an endophytic fungus called *Piriformospora indica* increases the production of ascorbic acid and the activity of antioxidants. It also increases the ratios of K+/Na+ and Ca2+/Na+, sugars, and free amino acids in barley plants [41]. In a study, Sun *et al*. [42] reported that an endophyte, *Piriformospora indica*, had shown drought tolerance in Arabidopsis and Chinese cabbage by stimulating the drought stress-related genes. In another study, *Trichoderma hamatum*, an endophytic fungus from *Theobroma gileri* was reported to delay the drought response in *Theobroma cacao* [43]. In certain cases, abiotic stresses cause membranes to rupture due to variations in lipid composition, and many studies show that endophytic fungi can prevent electrolyte leakage by inducing lipid composition in the cell membrane [44]. Abscisic acid (ABA) is known as the stress hormone, which causes stomata closure, and certain endophytic fungi have the potential to reduce ABA levels [45].

Biocontrol agent

The major threat to agricultural output is plant disease. With the emergence of fungicide-resistant pathogens and their impact on the environment, the number of chemicals used to control plant pathogens has been reduced. To overcome this problem, researchers have been focusing on endophytic fungi as a biocontrol agent. Endophytic fungi suppress plant diseases by producing antimicrobial compounds, limiting space and food, and boosting plant immunity. Many endophytic fungi have been reported as strong biocontrol agents against pathogens and insects [46]. Endophytic fungi produce secondary metabolites containing alkaloids, terpenoids, polyketones, steroids, peptides, phenols, flavonoids, quinols, etc. that show activity against pathogens and herbivores [47]. Seed treatment of tomato and cotton with an endophytic fungus, *Beauveri bassiana* induced resistance against the pathogenic fungi *Pythium myriotylum* and *Rhizoctonia solani* [48]. Kim *et al*. [49] have reported suppression of powdery mildew as well as aphids in cucumber plants by the endophytic fungus *Lecanicillium longisporum*. In a study, the endophytic fungus *Beauveri bassiana* could suppress downy mildew in grapes after leaf treatment [50]. Several endophytic *Alternaria* spp. have reported controlling pathogens like *Rhizoctonia solani*, *Fusarium oxysporum*, *Botrytis cinerea*, *Phytophthora capsici*, *Pseudomonas aeruginosa*, and *Plasmopara viticola* [51]. It has been reported that *Neotyphodium* sp. can control the mildew of *Elymus sibiricus* and also improve resistance to fungicides and pesticides [52]. Many endophytic fungi, such as *Beauveria bassiana*, *Isaria farinosa*, Clonostachys rosea, *Lecenicillium lecanii*, etc., could be used as entomopathogenic fungi against herbivore insects [53-54]. In a research González-Mas *et al*. [55] have reported that the endophytic fungi *Beauveria bassiana* and *Lecanicillium lecanii* reduce the feeding habits and reproduction of *Aphis gossypii* on the cotton plant. There has been a report that *Bauveria bassiana* could control the white stem weevil and coffee berry borer [56]. Mycofumigation is also another biocontrol technique using endophytic fungi to control the postharvest disease of fruits and vegetables [57].

Plant growth promotion

Several endophytic fungi have been studied for their plant growth-promoting potentials to the host plant and also for other crop plants [58]. Fungal endophytes improve the uptake of macronutrients from soil and organic matter, increase biomass, and restrict herbivores from eating plants, according to recent studies [59]. The corn plant was reported to increase its yield significantly when treated with *Metarhizium brunneum* [60]. The phytohormone gibberellin induces seed germination, stem elongation, fruit formation, and senescence [61]. Many endophytic fungi, such as *Penicillium citrinum*, *Aspergillus fumigatus*, *Cladosporium sphaerospermum*, etc., generate gibberellin [62]. Auxin hormones regulate plant growth, shoot and root development, tropism, cell division and elongation, and differentiation of tissues [63]. The endophytic fungi *Phoma glomerata*, *Paecilomyces formosus*, and *Penicillium* sp., have been reported to produce indole 3-acetic acid (IAA) and gibberellic acid (GA) [64]. In an investigation, the application of *Vicia faba* with *Beauveria brongniartii*, *B. bassiana*, *Metarhizium bassiana*, and *Purpureocillium lilacinum* increased overall growth [65]. Tomato plants have also been shown to enhance height, weight, and root lengths after being treated with *Metarhizium anisopliae* [66]. Jaber and Alananbeh [67] have also suggested that *Beauveria bassiana* and *Metarhizium brunneum* improve the health of sweet pepper (*Capsicum annum*). Behie and Bidochka [68] have shown that *Metarizium brunneum*, *Beauveria bassiana*, and *Lecanicillium lecanii* could serve as biofertilizers as they can supply a large amount of nitrogen to crop plants after infecting *Galleria mellonella* larvae. Siderophores are small, iron-chelating molecules that promote plant growth and are shown to be produced by the endophytic fungi *Trichoderma koningii*, *Trichoderma harzianum*, and *Macrophomina phaseolina* [69].

CONCLUSION

This review highlighted the importance of endophytic fungi in the agriculture sector, their role in providing sustainable agriculture, and how they can restore soil health. By giving more importance to the research of endophytic fungi, various novel compounds will be revealed that can solve problems relating to crop production, environmental degradation, and medicine in an eco-friendly, cost-effective, and little time-consuming manner. Due to our decreasing life span and the development of new diseases, eating healthier foods free of chemicals is our main concern. The demand for organic food products has increased tremendously in the last decade, and endophytic fungi could play an important role. The application of endophytic fungi in agriculture as a biocontrol agent, biofertilizer, soil enricher, and biostimulant indicates its prospects for in-depth research. Organic farming practices have been increasing over the last two decades due to their chemical-free and pollution-free nature. Exploration of endophytic fungi for their use in agriculture is the most unexplored area of research. The efficacy of endophytic fungi in agriculture could be increased with the use of sophisticated instruments.

LITERATURE CITED

1. Zivanovic A, Rodgers L. 2019. The role of fungal endophytes in plant pathogen resistance. *Bios* 89(4): 192-197.
2. Vega FE, Simpkins A, Aime MC, Posada F, Peterson SW, Rehner SA, Infante F, Arnold AE. 2010. Fungal endophyte diversity in coffee plants from Colombia, Hawai'i, Mexico and Puerto Rico. *Fungal Ecology* 3(3): 122-138.
3. Sun X, Guo LD. 2012. Endophytic fungal diversity: review of traditional and molecular techniques. *Mycology* 3(1): 65-76.
4. Khare E, Mishra J, Arora NK. 2018. Multifaceted interactions between endophytes and plant: developments and prospects. *Frontiers in Microbiology* 9: 2732.
5. Petrini O, Andrews JH, Hirano SS. 1991. *Microbial Ecology of Leaves*. Spring-Verlag, New York. pp 179-197.
6. Bhardwaj M, Dhiman M. 2019. Growth and performance of organic farming in India: What could be the future prospects? *Growth* 20: 1-8.
7. Paull J. 2023. The global growth and evolution of organic agriculture. *In*: Research Advancements in Organic Farming. Nova Science. pp 1-17.
8. Chhonkar PK. 2008. Organic farming and its relevance in India. Scientific Publishers, Jodhpur, India. pp 5-33.
9. Baron NC, Rigobelo EC. 2022. Endophytic fungi: A tool for plant growth promotion and sustainable agriculture. *Mycology* 13(1): 39-55.
10. Zikankuba VL, Mwanyika G, Ntwenya JE, James A. 2019. Pesticide regulations and their malpractice implications on food and environment safety. *Cogent Food and Agriculture* 5(1): 1601544.
11. Kulkarni S, Goswami A. 2019. Effect of excess fertilizers and nutrients: a review on impact on plants and human population. In Proceedings of International Conference on Sustainable Computing in Science, Technology and Management (SUSCOM), Amity University Rajasthan, Jaipur, India.
12. Katoch M, Pull S. 2017. Endophytic fungi associated with *Monarda citriodora*, an aromatic and medicinal plant and their biocontrol potential. *Pharmaceutical Biology* 55(1): 1528-1535.
13. Manzar N, Kashyap AS, Goutam RS, Rajawat MVS, Sharma PK, Sharma SK, Singh HV. 2022. *Trichoderma*: Advent of versatile biocontrol agent, its secrets and insights into mechanism of biocontrol potential. *Sustainability* 14(19): 12786.

14. Latz MA, Jensen B, Collinge DB, Jørgensen HJ. 2018. Endophytic fungi as biocontrol agents: elucidating mechanisms in disease suppression. *Plant Ecology and Diversity* 11(5/6): 555-567.
15. Lahlali R, Hijri M. 2010. Screening, identification and evaluation of potential biocontrol fungal endophytes against *Rhizoctonia solani* AG_3 on potato plants. *FEMS Microbiology Letters* 311(2): 152-159.
16. Bamisile BS, Akutse KS, Siddiqui JA, Xu Y. 2021. Model application of entomopathogenic fungi as alternatives to chemical pesticides: Prospects, challenges, and insights for next-generation sustainable agriculture. *Frontiers in Plant Science* 12: 741804.
17. Misra M, Sachan A, Sachan SG. 2021. Role of fungal endophytes in the green synthesis of nanoparticles and the mechanism. *In*: Fungi Bio-Prospects in Sustainable Agriculture, Environment and Nano-technology. Academic Press. pp 489-513.
18. Bamisile BS, Dash CK, Akutse KS, Keppanan R, Wang L. 2018. Fungal endophytes: beyond herbivore management. *Frontiers in Microbiology* 9: 544.
19. Saikkonen K, Wäli P, Helander M, Faeth SH. 2004. Evolution of endophyte–plant symbioses. *Trends in Plant Science* 9(6): 275-280.
20. Zhou WN, White JF, Soares MA, Torres MS, Zhou ZP, Li HY. 2015. Diversity of fungi associated with plants growing in geothermal ecosystems and evaluation of their capacities to enhance thermotolerance of host plants. *Journal of Plant Interactions* 10(1): 305-314.
21. Rashmi M, Kushveer JS, Sarma VV. 2019. A worldwide list of endophytic fungi with notes on ecology and diversity. *Mycosphere* 10(1): 798-1079.
22. Porras-Alfaro A, Bayman P. 2011. Hidden fungi, emergent properties: endophytes and microbiomes. *Annual Review of Phytopathology* 49: 291-315.
23. Chhipa H, Deshmukh SK. 2019. Fungal endophytes: rising tools in sustainable agriculture production. Endophytes and Secondary Metabolites. Springer International Publishing AG, Cham. pp 1-24.
24. Sir EB, Hladki AI, Parrado MF, Romero AI. 2012. Biodiversity of Xylariaceae (Ascomycota) and their hosts in protected areas from Tucumán (Argentina). *Kurtziana* 37(2): 35-48.
25. Dong C, Wang L, Li Q, Shang Q. 2021. Epiphytic and endophytic fungal communities of tomato plants. *Horticultural Plant Journal* 7(1): 38-48.
26. Yao Y, Zhang M. 2015. Subnational leaders and economic growth: evidence from Chinese cities. *Jr. Econ. Growth* 20: 405-436. https://doi.org/10.1007/s10887-015-9116-1
27. Scannerini S, Fusconi A, Mucciarelli M. 2002. The effect of endophytic fungi on host plant morphogenesis. *Symbiosis: Mechanisms and Model Systems*. pp 425-447.
28. Savci S. 2012. An agricultural pollutant: chemical fertilizer. *International Journal of Environmental Science and Development* 3(1): 73.
29. Ray P, Lakshmanan V, Labbé JL, Craven KD. 2020. Microbe to microbiome: A paradigm shift in the application of microorganisms for sustainable agriculture. *Frontiers in Microbiology* 11: 622926.
30. Tarafdar M, Bahadur V, Rana S, Singh RK. 2022. A review: Abiotic stress on transpiration, stomatal diffusive resistance and photosynthetic rate. *Pharma. Innov. Jr.* 11: 1632-1635.
31. Bilal L, Asaf S, Hamayun M, Gul H, Iqbal A, Ullah I, Lee IJ, Hussain A. 2018. Plant growth promoting endophytic fungi *Asprgillus fumigatus* TS1 and *Fusarium proliferatum* BRL1 produce gibberellins and regulates plant endogenous hormones. *Symbiosis* 76: 117-127.
32. Hamayun M, Afzal Khan S, Ahmad N, Tang DS, Kang SM, Na CI, Sohn EY, Hwang YH, Shin DS, Lee BH, Kim JG, Lee IJ. 2009. *Cladosporium sphaerospermum* as a new plant growth-promoting endophyte from the roots of *Glycine max* (L.) Merr. *World Journal of Microbiology and Biotechnology* 25: 627-632.
33. Hassan SED. 2017. Plant growth-promoting activities for bacterial and fungal endophytes isolated from medicinal plant of *Teucrium polium* L. *Journal of Advanced Research* 8(6): 687-695.
34. Rauf M, Awais M, Ud-Din A, Ali K, Gul H, Rahman MM, Hamayun M, Arif M. 2021. Molecular mechanisms of the 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase producing *Trichoderma asperellum* MAP1 in enhancing wheat tolerance to waterlogging stress. *Frontiers in Plant Science* 11: 614971.
35. Hamayun M, Hussain A, Iqbal A, Khan SA, Khan MA, Lee IJ. 2021. An endophytic fungus *Gliocladium cibotii* regulates metabolic and antioxidant system of *Glycine max* and *Helianthus annuus* under heat stress. *Polish Journal of Environmental Studies* 30(2): 1631-1640.
36. Arora NK, Fatima T, Mishra I, Verma M, Mishra J, Mishra V. 2018. Environmental sustainability: challenges and viable solutions. *Environmental Sustainability* 1: 309-340.
37. Yadav S, Modi P, Dave A, Vijapura A, Patel D, Patel M. 2020. Effect of abiotic stress on crops. *Sustainable Crop Production* 3. doi:10.5772/intechopen.88434.
38. Lata R, Chowdhury S, Gond SK, White Jr JF. 2018. Induction of abiotic stress tolerance in plants by endophytic microbes. *Letters in Applied Microbiology* 66(4): 268-276.
39. Hussain SS, Mehnaz S, Siddique KH. 2018. Harnessing the plant microbiome for improved abiotic stress tolerance. *Plant Microbiome: Stress Response*. pp 21-43.
40. Chhipa H, Deshmukh SK. 2019. Fungal endophytes: rising tools in sustainable agriculture production. *In*: (Eds) Jha S. Endophytes and Secondary Metabolites. Reference Series in Phytochemistry. Springer, Cham. https://doi.org/10.1007/978-3-319-90484-9_26
41. Ghabooli M. 2014. Effect of *Piriformospora indica* inoculation on some physiological traits of barley (*Hordeum vulgare*) under salt stress. *Chemistry of Natural Compounds* 50(6): 1082-1087.
42. Sun C, Johnson JM, Cai D, Sherameti I, Oelmüller R, Lou B. 2010. *Piriformospora indica* confers drought tolerance in Chinese cabbage leaves by stimulating antioxidant enzymes, the expression of drought-related genes and the plastid-localized CAS protein. *Journal of Plant Physiology* 167(12): 1009-1017.

43. Bae H, Sicher RC, Kim MS, Kim SH, Strem MD, Melnick RL, Bailey BA. 2009. The beneficial endophyte *Trichoderma hamatum* isolate DIS 219b promotes growth and delays the onset of the drought response in *Theobroma cacao*. *Journal of Experimental Botany* 60(11): 3279-3295.
44. Raza A, Mehmood SS, Shah T, Zou X, Yan L, Zhang X, Khan RSA. 2019. Applications of molecular markers to develop resistance against abiotic stresses in wheat. *Wheat Production in Changing Environments: Responses, Adaptation and Tolerance*. pp 393-420.
45. Khan AL, Hussain J, Al-Harrasi A, Al-Rawahi A, Lee IJ. 2015. Endophytic fungi: Resource for gibberellins and crop abiotic stress resistance. *Critical Reviews in Biotechnology* 35(1): 62-74.
46. Jaber LR, Ownley BH. 2018. Can we use entomopathogenic fungi as endophytes for dual biological control of insect pests and plant pathogens? *Biological Control* 116: 36-45.
47. Singh D, Thapa S, Mahawar H, Kumar D, Geat N, Singh SK. 2022. Prospecting potential of endophytes for modulation of biosynthesis of therapeutic bioactive secondary metabolites and plant growth promotion of medicinal and aromatic plants. *Antonie Van Leeuwenhoek* 115(6): 699-730.
48. Ownley BH, Griffin MR, Klingeman WE, Gwinn KD, Moulton JK, Pereira RM. 2008. *Beauveria bassiana*: endophytic colonization and plant disease control. *Journal of Invertebrate Pathology* 98(3): 267-270.
49. Kim JJ, Goettel MS, Gillespie DR. 2010. Evaluation of *Lecanicillium longisporum*, Vertalec® against the cotton aphid, *Aphis gossypii*, and cucumber powdery mildew, *Sphaerotheca fuliginea* in a greenhouse environment. *Crop Protection* 29(6): 540-544.
50. Jaber LR. 2015. Grapevine leaf tissue colonization by the fungal entomopathogen *Beauveria bassiana* sl and its effect against downy mildew. *BioControl* 60: 103-112.
51. Ortega HE, Torres-Mendoza D, Cubilla-Rios L. 2020. Patents on endophytic fungi for agriculture and bio-and phytoremediation applications. *Microorganisms* 8(8): 1237.
52. Li XZ, Song ML, Yao X, Chai Q, Simpson WR, Li CJ, Nan ZB. 2017. The effect of seed-borne fungi and *Epichloë* endophyte on seed germination and biomass of *Elymus sibiricus*. *Frontiers in Microbiology* 8: 2488.
53. Vega FE, Posada F, Aime MC, Pava-Ripoll M, Infante F, Rehner SA. 2008. Entomopathogenic fungal endophytes. *Biological Control* 46(1): 72-82.
54. Bamisile BS, Akutse KS, Siddiqui JA, Xu Y. 2021. Model application of entomopathogenic fungi as alternatives to chemical pesticides: Prospects, challenges, and insights for next-generation sustainable agriculture. *Front. Plant Science* 12: 741804. doi: 10.3389/fpls.2021.741804
55. González-Mas N, Quesada-Moraga E, Plaza M, Fereres A, Moreno A. 2019. Changes in feeding behaviour are not related to the reduction in the transmission rate of plant viruses by *Aphis gossypii* (Homoptera: Aphididae) to melon plants colonized by *Beauveria bassiana* (Ascomycota: Hypocreales). *Biological Control* 130: 95-103.
56. Mascarin GM, Jaronski ST. 2016. The production and uses of *Beauveria bassiana* as a microbial insecticide. *World Journal of Microbiology and Biotechnology* 32: 1-26.
57. Kaddes A, Fauconnier ML, Sassi K, Nasraoui B, Jijakli MH. 2019. Endophytic fungal volatile compounds as solution for sustainable agriculture. *Molecules* 24(6): 1065.
58. Rana KL, Kour D, Kaur T, Devi R, Yadav AN, Yadav N, Harcharan SD, Saxena AK. 2020. Endophytic microbes: biodiversity, plant growth-promoting mechanisms and potential applications for agricultural sustainability. *Antonie Van Leeuwenhoek* 113: 1075-1107.
59. Prakash O, Sharma R, Rahi P, Karthikeyan N. 2015. Role of microorganisms in plant nutrition and health. In: (Eds) Rakshit A., Singh H. B., Sen A. Nutrient Use Efficiency: from Basics to Advances. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2169-2_9
60. Liao X, O'Brien TR, Fang W, St. Leger RJ. 2014. The plant beneficial effects of *Metarhizium* species correlate with their association with roots. *Applied Microbiology and Biotechnology* 98: 7089-7096.
61. Davies PJ. 2010. The plant hormones: Their nature, occurrence, and functions. Springer Netherlands. pp 1-15.
62. Rai M, Rathod D, Agarkar G, Dar M, Brestic M, Pastore GM, Junior MRM. 2014. Fungal growth promotor endophytes: A pragmatic approach towards sustainable food and agriculture. *Symbiosis* 62: 63-79.
63. Vanneste S, Friml J. 2009. Auxin: A trigger for change in plant development. *Cell* 136(6): 1005-1016.
64. Waqas M, Khan AL, Lee IJ. 2014. Bioactive chemical constituents produced by endophytes and effects on rice plant growth. *Journal of Plant Interactions* 9(1): 478-487.
65. Jaber LR, Enkerli J. 2017. Fungal entomopathogens as endophytes: can they promote plant growth? *Biocontrol Science and Technology* 27(1): 28-41.
66. Elena GJ, Beatriz PJ, Alejandro P, Lecuona RE. 2011. *Metarhizium anisopliae* (Metschnikoff) Sorokin promotes growth and has endophytic activity in tomato plants. *Adv. Biol. Research* 5(1): 22-27.
67. Jaber LR, Alananbeh KM. 2018. Fungal entomopathogens as endophytes reduce several species of *Fusarium* causing crown and root rot in sweet pepper (*Capsicum annuum* L.). *Biological Control* 126: 117-126.
68. Behie SW, Bidochka MJ. 2014. Nutrient transfer in plant-fungal symbioses. *Trends in Plant Science* 19: 734-740.
69. Rai S, Solanki MK. 2023. Beneficial endophytic *Trichoderma* functions in plant health management. *In*: *Microbial Endophytes and Plant Growth*. Academic Press. pp 233-244.