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Tiny Giants Endophytes in Sustainable Agriculture: Trends and Prospects

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Abstract

Changing understanding of endophytes in the realm of agriculture suggests the possibility of improving soil health and productivity, as well as the overall environmental sustainability of agriculture. These non-pathogenic microorganisms living in a plant are capable of conferring stress tolerance, promoting growth, and suppressing pathogens. Nevertheless, navigating regulatory barriers and streamlining application techniques pose challenges. To maximize their agricultural utility, future research should focus on exploring new strains, optimizing application techniques, and integrating endophytes into crop breeding programs. Leveraging endophytes may further lead to the developing of sustainable agriculture and reduce many concerns related to global food security.

Keywords: Endophytes, Agriculture, Crop Productivity, Stress Tolerance, Pathogen Suppression, Sustainable Agriculture

1. Introduction

In recent years, there has been a growing interest in harnessing endophytic microorganisms from plant tissues that can produce secondary metabolites for their host and have other functions that can affect plant growth and resist pathogens. This makes endophytic microorganisms a very promising tool for the biocontrol of plant pathogens and plant growth promotion, which has become extremely significant for sustainable agriculture [1–4]. These metabolites, such as phenols, and polyketides, which are saponins, alkaloids, and some terpenoids, have various bioactive attributes and can mitigate biotic and also abiotic stresses [5]. Endophytic microorganisms promoting nutrient uptake, stress tolerance, as well as disease resistance/suppression in host plants, and even environmental clean-up, have been shown to increase agricultural yields [6–8]. By examining many metabolic pathways of endophytic bacteria, novel agrochemicals for disease prevention and sustainable agriculture can be improved. The release of some bioactive substances by them can both protect plants from diseases and promote plant growth once colonised in healthy plant tissues [6,8–10]. Additionally, these microbes can offer enhanced drought, moisture, and salinity tolerances, making them very appropriate for farming on marginal terrains [11]. They produce phytohormones, physiologically active substances, and some enzymes that can improve plant health and, productivity [12]. The use of endophytes as bioinoculants has the potential to improve crop production and lessen the need for artificial fertilisers and pesticides, providing a sustainable substitute for conventional farming methods [13,14]. Medicinal, agricultural, industrial, as well as environmental biotechnological applications can all greatly benefit from the chemical and also, functional diversity of some natural compounds derived from endophytes [15]. Additionally, the efficiency, as well as efficacy of endophytic inoculants, can be improved by the engineering of some microbial communities through genome editing and microbiome engineering, promoting high yield, disease resistance, and nutrient cycling in plants [5]. It is somehow possibly possible to design novel agrochemicals for disease control and sustainable agriculture by investigating the many metabolic pathways of endophytic bacteria [16]. This review delves into how microbes can improve plant growth, lessen reliance on agrochemicals, and pave the way for the creation of innovative, environmentally friendly agrochemicals for sustainable agriculture.

2. Diversity and Ecology of Endophytes

The diversity and pliability across different plant species and ecosystems are remarkably featured by endophytic microorganisms. Endophyte diversity understanding and ecology are fundamental to exploiting their potential in sustainable agriculture. Increased research should be done to better understand endophyte diversity in a variety of plant species, including non-crop plants and those that live in arid climates, high elevations, and aquatic setting[6]. Variations in the environment, plant growth phases, and seasonal variations can all cause temporal variations in endophyte communities. To fully understand seasonal fluctuations in endophyte communities and how they affect plant health and productivity, long-term research is required [17]. There is a lack of knowledge regarding the time dynamics of endophyte colonization and diversity [18]. An additional investigation conducted by Saikia et al. revealed that the monsoon season is ideal for collecting samples, as it is when the greatest number of endophyte populations are isolated [19]. All these results highlight the temporal dynamics in endophytic communities and the requisite of fundamental study to fully comprehend their effects on the productivity and health of plants. Environmental building blocks like soil characteristics, climate and geographic location can have ramifications on endophyte diversity and composition [20]. However, the degree to which these environmental factors affect endophytes at diverse spatial scales is not utterly understood [21]. The biogeography of endophytes and the primary environmental factors shaping endophyte diversity need comparative research embracing a plethora of ecosystems and geographical areas [22]. Endophytes generate complex microbial populations with significant ecological consequences by interacting with other microorganisms in plant tissues. Plant health and ecosystem function are significantly impacted by the way plant roots interact with rhizosphere bacteria and fungi [23]. Plant development and nutrient absorption are positively impacted by symbiotic bacteria and fungi, such as mycorrhizae and Rhizobia [24]. Endophytic microorganisms colonize various parts of plants and can have mutualistic, commensal or symbiotic relationships with their hosts [25,26]. These endophytes are crucial for controlling plant growth, enhancing host resilience, and shielding plants from biotic and abiotic stressors [27]. Through direct sequencing of DNA from plant tissues, metagenomic methods offer strong tools for understanding endophyte communities[28]. These techniques get over the drawbacks of conventional culture-based methods in capturing the complete range of endophytes, especially those that are picky or non-culturable. Nonetheless, the development and optimisation of bioinformatic pipelines remain necessary for the analysis of endophyte metagenomic data and the extraction of significant ecological insights. Bacterial and fungal endophytes and a variety of functional traits could be used in biotechnological applications such as bioremediation, medicines, and agriculture. These microbes symbiotically coexist with their hosts in healthy plant tissues, generating bioactive chemicals that boost stress tolerance, guard against infections, and encourage plant development. The mechanisms behind the vertical and horizontal transfer of endophytes in plants remain unclear, necessitating additional study. Comprehending the processes of transmission is essential to comprehending the establishment and persistence of endophyte populations within plant populations. Vertical transmission refers to the transmission of endophytes from parent to offspring, either through seeds or pollen. Horizontal transmission, on the other hand, involves the transmission of endophytes between unrelated plants, often through the soil, atmosphere, or insects [35,36]. Scholars can learn more about the processes that influence endophyte communities and their relationships with plants by examining the various pathways by which bacteria can colonise plants, including both vertical and horizontal transmission channels. Different endophytes have different levels of host specialisation; some are highly specialised to specific plant species or genera, while others are more widely distributed. Endophyte host selectivity and specificity are influenced by poorly defined variables [40]. To further understand endophyte-host interactions and specificity, research should focus on identifying the genetic, physiological, and ecological aspects involved. Scientists can improve our knowledge of endophyte ecology and diversity as well as harness their potential for environmentally friendly agriculture by filling in these research gaps.

3. Mechanisms of Endophyte-Plant Interaction

Several processes in the endophyte-plant interactions are essential for adequate plant development and stress resistance. Endophytes, soil-inhabiting fungi and bacteria that colonize plant cells without harming them facilitate nutrient fixation, phytohormone signalling, and secondary metabolite secretion [25,27]. Interactions are essential to fighting biotic and abiotic stress where biomolecules and phytohormones take the lead in disease control and stress responses [26]. Endophytic bacteria are important for disease resistance and wellness and are easily accessible to root systems; plant species and soil characteristics strongly affect the form’s recruitment [43]. Endophytic bacteria reinforce the plant’s defence reactions; they prevent pathogen use of your resources and tissues and promote plant health and resistance to tension, especially evident in rapidly changing climatic circumstances[44]. Endophytes utilize multiple strategies to benefit plants in various ways to develop grow better and alleviate stress. They are symbiotic microorganisms that live in plant tissues but do not cause harm and include bacteria and fungi [25,27,45]. Such endophytes influence plant growth and development by providing nitrogen fixation and producing phytohormones, supporting phytoremediation, and synthesizing bioactive compounds [46,47]. The interaction between the plants and endophytes may include a vast spectrum of physiological processes vital for plant growth and health. Nitrogen fixation, the phytohormone signal, the process of phytoremediation, and the synthesis of secondary metabolites belong to the processes initiated by bacteria and fungi [48,49]. These associations are necessary to mitigate microbial and environmental stress in plants, and biomolecules and growth hormones play a significant role as central regulators [50]. Rhizospheric endophytic bacteria are involved in promoting plant growth and ensuring health. These bacteria constitute a variety of progressive and retarding specialists [51]. Beneficial endophytic fungi help to regulate pathogenic fungi through metabolite synthesis, hormone signalling, and gene expression for a healthy plant and the suppression of illness [52]. For a healthy plant, fungal endophytes aid growth and stress resilience by releasing antifungal compounds and phytohormones for the preservation of disease and growth, which is another critical aspect in biocontrol and biostimulation; this relationship is of great concern in agriculture. These mechanisms should be understood extensively to enhance endophytes’ usage in biocontrol and further promote plant resilience in agricultural systems.

4. Functional Roles of Endophytes in Agriculture

"Agriculturally Important Microorganisms (AIMs) represent a wide range of microorganisms which include Plant Growth-Promoting Rhizobacteria (PGPR), Biocontrol Agents (BCA), Plant Growth-Promoting Fungi (PGPF), Actinomycetes, Mycorrhiza, and Endophytes" [53]. Microorganisms secreting key hormones, essential enzymes, prime factors, and active metabolites like phosphatases, siderophores, indoleacetic acid, antimicrobial metabolites of practical significance to sustainable agriculture and other plant growth-promoting traits of cold-adapted microorganisms can be properly utilized to naturally enhance the productivity of cultivated crops in these regions [54]. Extensive exploration of beneficial microorganisms from poorly explored habitats is still in its nascent stage, and the active search for better microbial isolates from exotic habitats with prospective sources of bioproducts could divulge some novel and promising isolates with unique functionalities suitable for use in sustainable agriculture practices [55]. Different types of microorganisms are known to exist in freshwater habitats. These microbes function similarly to the microorganisms found in soil and air. Freshwater, brackish, marine and terrestrial cyanobacteria (blue-green algae [BGA]) are a diverse group of prokaryotes and are also the most successful and oldest life forms on the planet. They play an important role in maintaining and improving soil fertility, increasing plant growth and yield as natural fertilisers, nutrient cycling, nitrogen (N_2) fixation and environmental protection [56]. Advantageous microorganisms called endophytes residing plants and bestow fertilisers, biopesticides and growth regulators to assist plants flourish. Table 1.0 highlights their different attributes and pursuits, which manifest their perspective in agricultural applications and stuff the market with beneficial microbial natural products.

Functionalities	**Endophytes**	**Properties**	**Host plant**	**Reference**
IAA production	*Aspergillus terreus*	Growth promotion	*Moringa oleifera*	[57,58]
Phosphate solubilisation	*Trichoderma harzianum*	Nutrient uptake	Hardwood bark	[59–61]
Biotic stress tolerance	*Paraphaeosphaeria sporulosa*	Antifungal	*Actinidia deliciosa*	[62,63]
GA production, pathogen resistance	*Aspergillus fumigatus*	Antifungal	*Glycine max*, *Zea mays*	[64,65]
General growth, pest resistance	*Beauveria bassiana*	Antifungal	*Vitis vinifera*, wheat	[66–69]
General growth, hormone production	*Colletotrichum tofieldiae*	Growth promotion	*Arabidopsis thaliana*	[70]
General growth, IAA production, N, Ca, Mg, Fe accumulation	*Diaporthe* sp.	Growth promotion Nutrient uptake	*Festuca rubra*	[71]
IAA production, pathogen resistance	*Aspergillus flavus*	Antifungal	*Euphorbia geniculata*	[72]

IAA production, salt tolerance	*Piriformospora indica*	Growth promotion Stress tolerance	Multiple	[73,74]
Jasmonic acid production	*Gilmaniella* sp	SAR, hypersensitive response	*Atractylodes lancea*	[75]
N & P accumulation	*Phomopsis liquidambari*	Bio-fertilization, Nutrient uptake	*Bischofia polycarpa*	[76]
P solubilisation, IAA production, Ca accumulation	*Aspergillus niger*	Bio-fertilization, Growth promotion	*Arachis hypogaea*	[77,78]
P, K, Mg, Cu, Zn, Mn accumulation	*Glomus mosseae*	Bio-fertilization	Not reported	[79]
Biotic stress tolerance	*Bacillus subtillis*	Stress tolerant	Not reported	[80]
Auxin production, N fixation, Toleraance, Siderophore production	*Streptomyces* sp.	Growth Promotion	*Vigna radiata*	[81,82]
IAA production, N fixation	*Azospirillum brasilense*	Growth Promotion	*Oryza sativa*	[83,84]
Insect deterrent	*Bacillus thuringiensis*	SAR, hypersensitive response	*Zea mays*	[85]
K accumulation	*Ewingella americana*	Nutrient uptake	*Zea mays*	[86]
K accumulation	*Ewingella americana* *Pantoea agglomerans*	Nutrient uptake	*Zea mays*	[86]
N fixation, P solubilisation, Auxin Production	*Azospirillum brasilense*	Bio-fertilization	*Triticum aestivum*	[87,88]
S metabolism, N fixation, K accumulation, IAA Production	*Burkholderia* sp	Growth Promotion	*Beta vulgaris*	[89,90]
Siderophore	*Serratia marcescens*	Growth	*Achyranthes*	[91–93]

production, IAA production, ammonia production, general growth		Promotion	*aspera*	
Sulphur metabolism, reduced ROS accumulation, salt toleranc	*Enterobacter* sp.	SAR, hypersensitive response	*Indigofera argentea*	[94]
Zn, P accumulation, Hormone production	*Staphylococcus homimis*	Antifungal	*Vigna radiata*	[81]
Ethyl trans-9.10-epoxy-ll-oxoundecanoate (**1**), Ethyl 9-oxononanoate (**2**), Ethyl azelate (**3**), Hydroxydihydrobovolide (**4**).	*Epichloe typhina*	Antifungal	*Phleum pratense* L.	[95]
8,1’,5’-trihydroxy-3’,4’ dihydro-1’H-[2,4’]binapthalenyl-1,4,2’-trione (**5**)	Fungus L1930 (unidentified)	Insecticide	*Larix laricina* (Du Roi) K. Koch	[96]
Chitinase	*Bacillus cereus* strain 65	Antifungal	*Sinapis arvensis* L.	[97]
Phosphatase, Protease, Cellulase, Hemicellulases, Pectinolytic enzymes, Ligninase	*Hymenoscyphus ericae*	Phosphate solubilization, Protein breakdown, Cell wall lysis.	Ericoid plants	[98]
Indole-3-acetic acid (IAA) and 3β-hydroxy-ergosta-5-ene (**6**)	*Colletotrichum* sp. B501	Plant growth hormone	*Artemisia annua* L.	[99]
Phosphate solubilization	*Penicillium* sp.	Bio-fertilization	*Triticum aestivum* L.	[100]
3-Hydroxypropionic acid (**7**)	*Phomopsis phaseoli and Melanconium betulinum strains*	Nematicidal	*Broad leaved tree of tropical rainforest, Betula pendula Roth. And*	[101]

			Betula pubescens Ehrh.	
Volatile organic compounds	*Muscodor albus*	Mycofumigation	*Cinnamomum zeylanicum* Blume	[102]
Jasmonates, abscisic acid and phosphate solubilization	*Bacillus* sp., *Achromobacter* sp., *Alcaligenes* sp.	Plant growth and development	*Helianthus annuus* L.	[103]
Protease amylase, lipase, laccase, cellulase and pectinase.	*Various fungal species*	Enhance resistance of grasses to multiple stresses.	*Catharanthusroseus* L.(G. Don.), *Calophylluminophyllum* L., *Bixaorellana* L., and *Alpiniacalcarata.* Roscoe	[104]
Leu^7-surfactin (**8**)	*Bacillus mojavensis* RRC 101	Biocontrol of *Fusarium verticillioides*	*Bacopamonnieri* L.	[105]
Indole Acetic Acid (IAA)	*Rhodotorula* sp. and *Rhodosporidium* sp.	Plant growth	*Populus* L.	[106]
Gibberellins	*Penicillium* sp. M5.A and *Aspergillus* sp M1.5	Promote plant growth and development.	*Monochoria vaginalis* (Burm.f.) C. Presl ex Kunth	[107]
Siderophores	*Phaeotheca* sp. *Fusarium sp.*, *Penicillium* sp. and *Arthrinium sp.*	Antibacterial	*Pinus sylvestris* L. and *Rhododendron tomentosum* Harmaja	[108]
1,8-cineole (monoterpene) (**9**)	*Hypoxylon* sp.	Antimicrobial	*Perseaindica* (L.) Spreng.	[109]
Nitrogen fixation	*Rhizobium leguminosarum*	Biofertilization, increase rice yield.	*Oryza sativa* L.	[110]
Chitosanase, chitinase.	Xylariaceae sp., *Aureobasidium pullulans*, *Colletotrichum*sp., *Lasiodiplodia theobromae*, *Phomopsis* sp. and *Fusarium* sp., *Botrytis* sp.,	Pathogenesis related proteins, phytoalexins and proteinase inhibitors in plants. Acts	Leaves of different tree species of Western Ghats.	[111]

	Trichoderma sp., *Alternaria*sp., *Nodulisporium gregarium*, *Nigrospora oryzae*, *Drechslera* sp., *Pithomyces* sp. *Sordaria* sp. and *Pestalotiopsis* sp.	against phytophagous nematodes and plant pathogenic fungi.		
Phosphate solubilization	*Penicillium* sp.	Bio-fertilization	*Camellia sinensis* (L.) Kuntze	[112]
Phosphatases, Siderophores, Nitrogen fixation	*Rahnella* sp. and *Pseudomonas* sp.	Bio-fertilization	*Musa* L.	[113]
Siderophores	*Streptomyces* sp. GMKU 3100	Promote plant growth	*Oryza sativa* L	[114]
Plant growth promoting factors and reduce cadmium toxicity	*Piriformospora indica*	Enhance plant growth in cadmium toxic soil.	*Triticum aestivum* L.	[115]
Gibberellins and Indole acetic Acid	*Penicillium* sp. LWL3 and *Phoma glomerata* LWL2	Promote plant growth	*Cucumis sativus* L.	[116]
Plant growth promoting factors	*Enterobacter* sp. FD17	Enhancement of maize yield	*Zey mays* L.	[117]
Plant growth promoting factors	*Phoma* sp.	Bio-fertilization	*Tinospora cordifolia* (Thunb.) Miers and *Calotropisprocera* (Aiton) W.T. Aiton	[118]
Trichodemin	*Trichoderma brevicompactum*	Antifungal against phytopathogens	*Allium sativum* L.	[119]
Indole acetic acid, Gibberellins and Reactive oxygen species.	*Galactomyces geotrichum* WLL1	Promote growth of plants in heavy metal contaminated soil.	*Trapa japonica* Flerov	[120]
Not identified (ethyl acetate	*Aspergillus* sp. And *Emericella* sp.	Insecticidal properties	*Rhizophora mucronata* Lam.	[121]

extract)				
Plant Growth promotion and Resistance to heavy metals	*Phialocephala fortinii*, *Rhizodermea veluwensis*, and *Rhizoscyphus* sp.	Growth enhancement, Nutrient uptake, Decrease Heavy metal concentration	*Clethra barbinervis* Sieb. Et Zucc.	[122]
Not identified (ethyl acetate extract)	*Several fungal isolates belonging to Ascomycota and few Zygomycota.*	Antifungal properties against root rot pathogens.	*Panax notoginseng* (Burkill) F. H. Chen ex C. Y. Wu & K. M. Feng	[123]
IAA, Siderophores, Phosphate solubilization	*Serratia* sp. , *Enterobacter* sp., *Acinetobacter* sp., *Pseudomonas* sp., *Stenotrophomonas* sp., *Agrobacterium* sp., *Ochrobactrum* sp., *Bacillus* sp. *and Tetrathiobacter* sp.	Plant growth promotion in *Zea mays.*	*Zingiber officinale* Roscoe	[124]

4. Challenges and Opportunities

Endophyte usage in agriculture represents a high potential, but there are several barriers it faces. Partially these are commercial and regulatory, and it is also related to poor understanding of the ecological roles of endophytes. This part of the paper aims to critically address these issues and offer possible solutions, including novel biotechnological solutions, interdisciplinary collaboration, and support for bio-based products.

However, the application of endophytes in agriculture faces various challenges, such as the low availability of microbial inoculants on the commercial market, regulatory concerns, and knowledge gaps regarding endophytes' ecological and physiological functions, some of which are mentioned in the literature [6,31,125]. Potential approaches to tackle these issues involve integrating research across different scientific disciplines, advancing biotechnological methods to enhance endophyte availability, and regulatory policies that support the widespread application of bio-based products [126]. As researchers continue to explore the diversity and functions of endophytic fungi, it is clear that several bioactive metabolites produced can enhance plant growth, protect against adverse conditions and other fungi, and control phytopathogenic fungi [127]. Therefore, appropriate knowledge, accessibility, and regulation of endophyte application should lead to expanded utilization across various agricultural sectors promoting crop yield and protecting the environment. However, useful the applications are, the utilization of endophytes in agricultural production comes with its challenges [11,128]. They include inadequate understanding of the ecological roles of endophytes, insufficient commercial microbial inoculant stocks [129], and regulatory barriers [130]. Therefore, interdisciplinary efforts are imperative in advancing the endophyte research [131]. “Researchers studying endophytes face difficulty in isolating underrepresented endophytes due to the vast diversity of plant microbiomes[132], a tendency to focus on well-known models in plant-fungal-stress combinations rather than exploring less studied factors[133], and the need for novel approaches in genotyping and phenotyping to consider the plant-endophyte holobiont for breeding programs” [134]. Additionally, one of the conditions for the development of breeding endophytes is the necessity for a new approach in genotyping and phenotyping that takes into account the plant-endophyte holobiont [135]. Furthermore, the complexity of the relationship between endophytes with a host plant and a microbiome does not allow the obtained data to be used in practice. It is recommended to use CRISPR/Cas9 systems, nanoparticles, and multi-omics that would allow the reconstruction of endophyte exploration and interaction with host plants [136]. Challenges in studying endophytes include understanding genetic nature, nutrient acquisition, host interactions, stability effects, and differences between bacterial and fungal endophytes for agricultural applications [137].

A holistic approach integrating advanced technologies, improved knowledge of plant ecology, and interdisciplinary collaboration is essential to fully harness the potential of endophytes and address weed management challenges.

5. Collaborative Networks and Funding opportunities

Globally collaborative networks and funding opportunities in endophyte research have acquired significant concentration [129,138]. As highlighted in various studies, these unified networks play a pertinent role in gaining ground in endophyte research, [139–141]. Boosting crop productivity, resilience, and sustainability collaborative efforts are pivotal to exploiting the full potential of endophytes [126,128,129,140,142]. “These networks involve chemists, mycologists, and other experts working together to understand the biology of endophytic fungi, optimize metabolite production, and explore novel bioactive compounds. Additionally, funding is essential for high-quality outcomes research in this field” [143]. Endophytic bacteria and fungi play fundamental roles in stress tolerance, plant health, and bioremediation field [144,145]. Endophytes yielding these bioactive compounds have potential applications in agriculture, pharmaceuticals, and environmental remediation. Funding opportunities in this field are crucial to further understanding the mechanisms of endophytes, developing sustainable agricultural practices, and addressing global health challenges. “Establishing virtual research centres, like the one in Brazil, can leverage diverse scientific expertise and attract investments from both government and private sectors” [146]. “Funding sources such as government ministries and foundations, like the German Federal Ministry for Economic Cooperation and Development and the Rockefeller Foundation, are instrumental in supporting research endeavours" [147]. The benefits like phytoremediation technologies, improving plant nutrition, development, and resilience to a range of stresses demonstrated by endophytes can be achieved only through cooperative efforts and funding. “Additionally, endophytic microorganisms have been a rich source of bioactive compounds with potential applications in medicine, agriculture, and the food industry, highlighting the importance of funding for further exploration and development” [149]. The key to understanding effective agricultural application is the interaction of endophytes with the host plants. Research on endophytes yielding bioactive compounds with a wide range of uses in industry, agriculture, and medicine can be achieved only by funding and collaborative networks, including government grants and foundations which could fuel research into their pharmaceutical and environmental potential, driving sustainable agriculture and innovative biotechnology.

6. Innovative Technologies and Methodologies

In endophyte research, innovative technologies and methodologies conceal a wide range of strategies meant to scrutinize the various competencies of these microorganisms. Modern genomic technologies are essential for unravelling the complicated interaction between plants and endophytes and for stress tolerance, helping host plant growth promotion and nutrient mobilization [152]. Genome sequencing and next-generation sequencing are employed to identify potent endophytes and understand beneficial plant-endophyte interactions [153]. Immunological methods are still essential for the precise and timely identification of endophytes despite the development of molecular approaches. The widespread application of immunological methods in lab and field settings is made possible by commercial diagnostic kits. Endophyte research employs innovative technologies and methodologies including DNA-based techniques like genome sequencing, comparative genomics, and next-generation sequencing to identify potent endophytic bacterial agents and explore plant-endophyte interactions [154]. Furthermore, a novel technique for extracting information about the endophytic microbiome from plant transcriptome data has been created, making it possible to gain a thorough understanding of the microbial communities found within the plant field[155]. Compared with conventional culturing methods, culture-free techniques such as next-generation sequencing have become more popular because of their capacity to identify higher levels of microbial diversity, which offers important insights into endophyte ecology [156]. Molecular methods have been crucial in researching endophytes, unveiling their structural diversity and functions. Metagenomics on the other hand offer a culture-independent approach to characterize ambient microbes and discover novel traits for agricultural and industrial applications [47,157]. All these promotions underscore the importance of cutting-edge tools in harnessing the bioactive potential of endophytic biotechnology [129]

7. Future Trajectory

Future directions in endophyte research encompass venturing the potentiality of endophytic microbes in diverse fields. Through improved nutrient cycling, bioremediation, and plant stress tolerance, endophytes have demonstrated potential in the agricultural sector. Furthermore, endophytic fungi are abundant producers of bioactive compounds with therapeutic attributes such as antibacterial and anticancer activities. “Searching for safe and effective antiviral agents against diseases like COVID-19 has also led researchers to investigate bioactive substances from endophytes” [150]. It is crucial to intensify bioprospecting endophytic novel secondary metabolites for sustainable agriculture and environmental remediation [158]. Harnessing the bioactive potential of endophytes through molecular mechanisms of endophyte-plant interactions can pave the way for innovative drug development, crop improvement, and environmental sustainability [159]. Future trajectories involve exploring the untapped potential of endophytes in various fields such as the utilization of multi-omics strategies that can contribute to discovering novel bioactive compounds for plant disease management [160]. Endophytes, especially fungal ones, show promise in agriculture, medicine, and industry due to their ability to produce bioactive compounds and enzymes with therapeutic and industrial applications Particularly fungal endophytes’ potential in agriculture, health, and business is exhibited by their ability to yield bioactive compounds and enzymes with industrial and medicinal uses [161]. The focus of the research should be on understanding the antimicrobial potential of endophytes against multidrug-resistant pathogens and deciphering their mode of action for drug development [145]. Furthermore, to completely understand the beneficent effects and prospective applications of fungal endophytes, research on dicot plants and in response to biotic stress needs to be broadened [133]. The effective implementation of endophytes in drug discovery for forming novel pharmacological metabolites can be achieved by exploring the molecular mechanisms of plant-endophyte interactions [162]. Developing tailored microbial consortia, optimising inoculation strategies, and exploring novel endophyte-host interactions are the key areas for future research [158,163]. Additionally, there is a need for collaborative efforts to fully unlock the potential of endophytes in enhancing crop productivity, resilience, and sustainability [164]. The urgency of concerted actions to harness the benefits of endophytes in shaping the agricultural landscape for better future research [165]. Therefore the integration of endophytes into mainstream practices is pivotal for the future of agriculture practices.

8. Conclusion

The prospects for the future include the promising role of endophytes in the future of the “agriculture of tomorrow. The review identifies future research directions, including the development of tailored microbial consortia, optimization of inoculation strategies and investigation into novel endophyte-host interactions, and the urgent need for collaborative work to unlock endophytes’ potential in shaping the future of agriculture. The coverage of the need for various new methodologies to analyze emerging work arrangements reflects the need for diverse methods in endophyte studies. Additionally, the descriptions of future research directions that are similar to those in metaphysics and the psychology of time illustrate the importance of exploring new fields to understand and harness the role of endophytes in agriculture. In conclusion, ‘the urgency for concerted efforts to unlock the full potential of endophytes in revolutionizing agriculture cannot be overstated’. By digging into interdisciplinary research, fostering innovation and optimizing strategies, researchers can leverage the strength of endophytes to escalate crop productivity, resilience, and sustainability. This endeavour holds promise not only for addressing current agricultural challenges but also for shaping a more sustainable and resilient future for food production worldwide.

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Conflicts of Interest

The authors declare no conflicts of interest.

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