

Fungal Biology

Bhim Pratap Singh ·
Ahmed M. Abdel-Azeem ·
Vibhav Gautam · Garima Singh ·
Santosh Kumar Singh *Editors*

Endophytic Fungi

The Hidden Sustainable Jewels for
the Pharmaceutical and Agricultural
Industries

 Springer

Fungal Biology

Series Editors

Vijai Kumar Gupta, Biorefining and Advanced Materials Research Center
Scotland's Rural College (SRUC), SRUC Barony Campus, Parkgate
Dumfries, Scotland, UK

Maria G. Tuohy, School of Natural Sciences
National University of Ireland Galway
Galway, Ireland

Fungal biology has an integral role to play in the development of the biotechnology and biomedical sectors. It has become a subject of increasing importance as new fungi and their associated biomolecules are identified. The interaction between fungi and their environment is central to many natural processes that occur in the biosphere. The hosts and habitats of these eukaryotic microorganisms are very diverse; fungi are present in every ecosystem on Earth. The fungal kingdom is equally diverse, consisting of seven different known phyla. Yet detailed knowledge is limited to relatively few species. The relationship between fungi and humans has been characterized by the juxtaposed viewpoints of fungi as infectious agents of much dread and their exploitation as highly versatile systems for a range of economically important biotechnological applications. Understanding the biology of different fungi in diverse ecosystems as well as their interactions with living and non-living is essential to underpin effective and innovative technological developments. This series will provide a detailed compendium of methods and information used to investigate different aspects of mycology, including fungal biology and biochemistry, genetics, phylogenetics, genomics, proteomics, molecular enzymology, and biotechnological applications in a manner that reflects the many recent developments of relevance to researchers and scientists investigating the Kingdom Fungi. Rapid screening techniques based on screening specific regions in the DNA of fungi have been used in species comparison and identification, and are now being extended across fungal phyla. The majorities of fungi are multicellular eukaryotic systems and therefore may be excellent model systems by which to answer fundamental biological questions. A greater understanding of the cell biology of these versatile eukaryotes will underpin efforts to engineer certain fungal species to provide novel cell factories for production of proteins for pharmaceutical applications. Renewed interest in all aspects of the biology and biotechnology of fungi may also enable the development of “one pot” microbial cell factories to meet consumer energy needs in the 21st century. To realize this potential and to truly understand the diversity and biology of these eukaryotes, continued development of scientific tools and techniques is essential. As a professional reference, this series will be very helpful to all people who work with fungi and should be useful both to academic institutions and research teams, as well as to teachers, and graduate and postgraduate students with its information on the continuous developments in fungal biology with the publication of each volume.

Bhim Pratap Singh
Ahmed M. Abdel-Azeem
Vibhav Gautam • Garima Singh
Santosh Kumar Singh
Editors

Endophytic Fungi

The Hidden Sustainable Jewels for the
Pharmaceutical and Agricultural Industries

Editors

Bhim Pratap Singh
Department of Agriculture
and Environmental Sciences
National Institute of Food Technology
Entrepreneurship and Management
(NIFTEM)
Sonapat, Haryana, India

Vibhav Gautam
Centre of Experimental Medicine
and Surgery
Institute of Medical Sciences
Banaras Hindu University
Varanasi, India

Santosh Kumar Singh
Centre of Experimental Medicine
and Surgery
Institute of Medical Sciences
Banaras Hindu University
Varanasi, India

Ahmed M. Abdel-Azeem
Botany and Microbiology Department
Faculty of Science
Suez Canal University
Ismailia, Egypt

Garima Singh
Department of Botany
Pachhunga University College
Mizoram University
Mizoram, India

ISSN 2198-7777

Fungal Biology

ISBN 978-3-031-49111-5

<https://doi.org/10.1007/978-3-031-49112-2>

ISSN 2198-7785 (electronic)

ISBN 978-3-031-49112-2 (eBook)

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Foreword

With immense joy and anticipation, I am delighted to present this extraordinary addition to Springer Nature's esteemed collection of works. This book opens the door to a realm of knowledge and exploration in the field of endophytic fungal research, inviting readers to comprehend the crucial role and significance of these fungi across various industries.

Encompassing contributions from distinguished scholars, this volume delves into a myriad of topics, ranging from the symbiotic relationships of endophytes with their hosts to their potential applications in agriculture and pharmaceuticals. The chapters are meticulously arranged to facilitate a comprehensive understanding of the roles and importance of endophytic fungi.

This book serves as an all-in-one solution for researchers and students engaged in the study of endophytic fungi, while also providing valuable reference material for professionals in the agriculture and pharmaceutical sectors. I extend my heartfelt appreciation to the editors and contributors who have poured their passion and expertise into laying the foundation for this remarkable volume. Their collective contributions enrich the academic discourse that shapes our world.

Lastly, I hope this book will inspire and empower readers to reach new heights of expertise in endophytic fungal research. May it ignite a spark of curiosity that leads to remarkable advancements in this field.

President, FAARD Foundation, Varanasi, India
Chancellor, Rani Lakshmi Bai Central Agricultural
University, Jhansi, India
Ex-Secretary, Department of Agriculture Research
and Education, Varanasi, India
Ex-Director General, Indian Council of Agricultural
Research, Varanasi, India
Ex-Vice Chancellor, Banaras Hindu University, Varanasi, India

Panjab Singh

Preface

Every book has a beginning, and this one is no exception. As we read the compiled chapters on various aspects of endophytic fungi, we are filled with their importance in the agriculture, health, and pharmaceutical industries. This preface captures the intentions and motivations driving us to bring book volume on *Endophytic Fungi: The Hidden Sustainable Jewels for the Pharmaceutical and Agricultural Industries*.

The genesis of this book lies in a confluence of experiences and questions. It is born out of countless conversations, moments of introspection, and a deep-seated desire to share insights that have shaped our understanding of the role of endophytic fungi in our life. In this book volume, you will find contributions from academicians working in the area and understanding the potential of endophytic fungi for sustainable development.

In this book, you will encounter chapters on broad aspects of endophytic fungi that may challenge, resonate, or inspire you and will generate your interest in this group of microorganisms. Others might encourage you to pause, reflect, and weave your interpretations into the narrative.

Ultimately, this book is a gesture of sharing – an offering of thoughts, perspectives, and facts on the latest developments on the role of endophytic fungi in agriculture and pharmaceutical industries. We hope readers will find the content appropriate for teaching and research.

Sonipat, Haryana, India
Ismailia, Egypt
Varanasi, India
Mizoram, India
Varanasi, India

Bhim Pratap Singh
Ahmed M. Abdel-Azeem
Vibhav Gautam
Garima Singh
Santosh Kumar Singh

Acknowledgments

The completion of this book volume marks a significant milestone, and it is with great humility and gratitude that we acknowledge the individuals whose contributions have made this achievement possible.

First and foremost, we extend our heartfelt appreciation to all the contributors who contributed to this book volume in the form of a book review. Your knowledge and invaluable insights have been instrumental in shaping the direction and depth of this book. We also thank the Springer Nature team for their continuous support and cooperation in bringing the volume in final shape.

Finally, we extend our gratitude to the readers who will embark on this journey. We hope the contents covered in this volume will match the reader's expectations.

Bhim Pratap Singh
Ahmed M. Abdel-Azeem
Vibhav Gautam
Garima Singh
Santosh Kumar Singh

Contents

1 Endophytic Fungi: Symbiotic Bioresource for Production of Plant Secondary Metabolites	1
Lovelesh Singh Saini, Swati Patel, Arti Gaur, Priti Warghane, Rashmi Saini, and Ashish Warghane	
1 Introduction.	2
2 Evolution of Endophytic Fungi in Plants	3
3 Biodiversity of Endophytic Fungi.	4
4 Interaction of Endophytic Fungi with Host Plant	5
4.1 For Sustainable Agriculture.	8
4.2 For Stress Management.	9
5 Production of Secondary Metabolites by Endophytic Fungi	9
5.1 Symbiotic Interaction	11
5.2 In Stress Conditions	12
6 Biotic Potential of Secondary Metabolites Produced by Endophytic Fungi	13
7 Application of Secondary Metabolites Produced from Symbiotic Fungi.	14
8 Challenges and Future Perspectives of Endophytic Fungi	15
9 Conclusion	15
References.	16
2 Fungal Endophytes as Potential Anticancer Candidate over Synthetic Drugs: Latest Development and Future Prospects	27
Chandrabhan Prajapati, Deepak Kumar, Vivek Ambastha, and Santosh Kumar Singh	
1 Introduction.	28
2 Fungal Endophyte.	30
3 Host-Fungal Endophyte Symbiosis.	32
4 Environmental and Biotic Clues Affecting the Survival of Endophytic Fungi.	33

5	Fungal-Endophyte-Derived Anticancer Compounds	33
6	Novel Resource for Anticancer Compounds: Fungi Endophytes	35
6.1	Alkaloids and Nitrogen Containing Heterocyclic Compounds	35
6.2	Coumarins	36
6.3	Lactones.	42
6.4	Peptides	42
6.5	Peroxides	42
6.6	Polyketides	43
6.7	Pyrans and Pyrones	43
6.8	Quinones	44
6.9	Steroids	44
6.10	Diterpenes	45
6.11	Triterpenes.	45
6.12	Miscellaneous	46
7	Conclusion and Future Prospects	48
	References.	49
3	Fungal Endophytes as an Alternative Natural Resource for the Discovery of Bioactive Compounds of Pharmacological Importance.	57
	Jyoti Lakshmi Hati Boruah, Deepjyoti Das, Parishmita Gogoi, Niraj Kumar, Babli Borah, Maini Borah, Pooja Talukdar, Cecilia Lulu, Priyanka Gogoi, Archana Yadav, Upasana Goswami, Bhim P. Singh, and Ratul Saikia	
1	Introduction.	58
2	Plant-Fungal Endophytes Associations.	58
3	Bioactive Metabolites from Endophytic Fungi.	59
4	Biological Properties of Endophytic Fungi.	59
4.1	Antibacterial Activity	61
4.2	Antifungal Activity	61
4.3	Antiviral Activity.	64
4.4	Antioxidant Activity	64
4.5	Anticancer Activity	68
4.6	Antidiabetic Properties	70
5	Conclusion and Future Prospect	72
	References.	73
4	Pharmaceutically Important Fungal Endophytes Associated with Mushrooms: Current Findings and Prospects.	79
	Swapnil C. Kamble and Mayuresh Dorle	
1	Introduction.	80
2	Endophytic Fungi in <i>Tricholoma matsutake</i> (Pine Mushroom or Matsutake Mushroom)	81
3	Endophytic Fungi in <i>Cordyceps sinensis</i> (Caterpillar Fungus)	82

4	Endophytic Fungi in <i>Cordyceps hawkesii</i> Gray (Fawn Vegetable Caterpillar)	84
5	Fungi in <i>Cordyceps militaris</i>	85
6	Endophytic Fungus (<i>Calcarisporium arbuscula</i>) from the Fruit Bodies of <i>Russulaceae</i>	90
7	Endophytes Screening in <i>Morchella crassipes</i>	91
8	Endophyte <i>Epicoccum sorghinum</i> Cultured in Host Mushroom <i>Thelephora ganbajun</i> (Ganba Fungus).	91
9	Conclusion and Prospects	92
	References.	93
5	Biological Synthesis of Nanoparticles from Fungal Endophytes and Their Application in Pharmaceutical Industries	99
	Kaizar J. Bharmal, Urvi R. Parlikar, and Joyita Sarkar	
1	Introduction.	100
2	Fabrication of Nanoparticles Using Endophytes	100
2.1	Fabrication of Silver Nanoparticles.	104
2.2	Fabrication of Zinc Nanoparticles.	105
2.3	Fabrication of Cobalt Nanoparticles	106
2.4	Fabrication of Iron Nanoparticles	107
2.5	Fabrication of Gold Nanoparticles	108
2.6	Fabrication of Copper Oxide Nanoparticles	108
2.7	Fabrication of Other Miscellaneous Nanoparticles.	109
3	Pharmaceutical Applications of Biosynthesized Nanoparticles Using Fungal Endophytes.	109
3.1	Antimicrobial Activity.	110
3.2	Antioxidant Activity	113
3.3	Anticancer/Tumor Activity	116
3.4	Wound-Healing Activity	120
4	Conclusion	121
	References.	122
6	Fungal Endophytes and Their Role in Postharvest Disease Management: An Overview	129
	Ramannagari Visweswara Maruthi Prasad, Kunuthuru Sivakumar, Charu Agnihotri, Shekhar Agnihotri, Ajit Kumar Passari, and Bhim Pratap Singh	
1	Introduction.	130
2	What Are Endophytes?	131
2.1	Bacterial Endophytes.	131
2.2	Fungal Endophytes	133
2.3	Actinobacterial Endophytes	134
3	Postharvest Losses (PHL) of Fruits and Vegetables in Food Supply Chain (FSC)	136

4	Postharvest Disease Management	138
4.1	Chemical Control	138
4.2	Biological Control	139
5	Conclusion	143
	References	145
7	Fungal Endophytes and Their Bioactive Compounds: An Overview of Potential Applications	153
	C. Lalbiaktluangi, Cherish Ranjan Mistry, Manveer Kaur, Navoneel Giri, Rashid Khalid Shaikh, Anish Nagar, Apurva Singh, Udita Sarkar, Sai Sravan K, Ojaswini Kalita, Richa Boro, Rahul Kumar, and Mukesh Kumar Yadav	
1	Introduction	154
2	Need to Explore Endophytic Fungi	155
3	Classification of Fungal Endophytes	155
4	Bioactive Compounds Isolated from Endophytic Fungi	156
5	Antimicrobial Activity of Endophytic Fungi and Associated Metabolites	158
6	Antiparasitic Compounds Derived from Fungal Endophytes	163
7	Anticancer Activity of Endophytic Fungi	164
8	Endophytic Fungi in Soil Remediation	170
	References	173
8	Therapeutic Potential of Fungal Endophyte-Derived Bioactive Compound in Protozoan Diseases	179
	Vishal Kumar Singh, Rahul Tiwari, Awnish Kumar, Rajneesh, Rohit Prasad Gupta, and Rajiv Kumar	
1	Introduction	180
2	Fungal Endophytes and Their Secondary Metabolites Having Antimalarial Properties	181
3	Fungal Endophytes and Their Secondary Metabolites Having Antileishmanial Properties	184
4	Future Perspective and Concluding Remarks	186
	References	187
9	Bioinformatics Approaches in Studying the Fungal Endophyte-Derived Bioactive Compounds with Pharmacological Relevance	191
	Satyendra Singh, Ketan Kumar, Abhishek Rao, and Vijay Kumar Prajapati	
1	Introduction	192
2	Interaction Between Fungal Endophyte and Plant	193
3	Fungal Endophyte: Drug Discovery Approach Through Bioinformatics	195
3.1	Compound Library Preparation: Through Literature Survey or Structure Designing by Tools Like ChemBioDraw	195

3.2	Ligand Preparation	196
3.3	Estimation of Druggable Property by ADME/T Prediction	197
3.4	Identification of Essential Drug Targets	199
3.5	Protein (Drug Target) Preparation and Grid Generation	199
3.6	Molecular Docking and Interaction Study	200
3.7	Estimation of Binding Energy	200
3.8	Molecular Dynamics Simulation (RMSD and RMSF Analysis)	201
4	Importance of Fungal Endophytes in Medicine	202
5	Conclusion and Future Prospective	203
	References	204
10	Omics-Based Approaches in Studying Fungal Endophytes and Their Associated Secondary Metabolites	209
	Poorvi Saini, Ashish Verma, Harshita Tiwari, Vishnu Mishra, and Vibhav Gautam	
1	Introduction	210
2	Genome Analysis	211
2.1	Multigenome Analysis	214
2.2	Metagenomics	215
3	Transcriptomics and Metatranscriptomics	216
4	Proteomics and Metaproteomics	217
5	Metabolomics	220
6	Conclusion	222
	References	223
11	Untapped Bioactive Compounds from Endophytic Fungi with Potential Antioxidant Activity	229
	Pranav Bhaskar, Divya Jain, and Reetesh Srivastava	
1	Introduction	230
2	Diversity and Distribution of Fungal Endophytes in Nature	231
3	Fungal Endophyte Interactions with Host Plants	232
3.1	Symbiotic Relationship with Host Plants	233
3.2	Commensalistic Association with the Host	235
4	Endophytic Fungi-Mediated Biotransformation of Secondary Metabolites	236
5	Endophytic Fungi Are a Natural Source of Antioxidants	237
6	Challenges in Endophytic-Fungi-Based Large-Scale Production of Antioxidants	238
6.1	Unculturable EFs	241
6.2	Inadequate and Unstable Yields	242
6.3	Intricate Plant-Endophyte Cross Talk	243

7	Strategies for Bioprospecting EFs for In Vitro Production of Antioxidant	243
7.1	Stimulation of Cryptic Pathway Genes in EFs by Genome Mining	243
7.2	EF Strain Improvement	244
7.3	Simulation and Optimization of the In Vitro Conditions	246
7.4	Use of Elicitors	247
7.5	Deep Learning and High-Throughput Approaches	248
8	Conclusion and Future Outlook	249
	References	250
12	Genetic, Epigenetic, and Physicochemical Strategies to Improve the Pharmacological Potential of Fungal Endophytes	259
	Mayur G. Naitam, Viabhav Kumar Upadhyay, A. K. Lavanya, Aman Jaiswal, Geeta Kumari, M. N. Jha, Himanshu Mahawar, and Rajeev Kaushik	
1	Introduction	260
2	Present Scenario of Pharmacological Drugs from Fungal Endophytes	262
3	Present Production Potential of Pharmacologically Important Endophytic Fungal Metabolites	264
4	Approaches for Improving Fungal Strains for Pharmacological Properties	266
4.1	Genetic Approach	266
4.2	Epigenetic Approach	268
4.3	Physicochemical Approach	271
5	Conclusion	272
6	Future Prospects	273
	References	274
13	Fungal Endophytes as Biocontrol Agents of Plant Pathogens: Recent Developments and Prospects	279
	Felicia Lalremruati, Nancy Lalhriatpuii, Awmpuizeli Fanai, Beirachhitha Bohia, Lalrokimi, Rosie Lalmuanpuii, Zirliannurga, Mukesh Kumar Yadav, Prashant Kumar Singh, and Zothanpuia	
1	Introduction	280
2	Fungal Endophytes	281
3	Isolation of Fungal Endophytes	282
4	Antagonism of Fungal Endophytes	284
5	Fungal Endophytes as Biocontrol Agents	288
6	Economic Impact of Plant Pathogens	289
7	Future Prospects	290
	References	291

14 Endophytic Fungi and the Health Benefits from Their Potential Bioactive Secondary Metabolites.	295
Mriganka Das, Sibashish Kityania, Rupshikha Nath, Rajat Nath, Deepa Nath, and Anupam Das Talukdar	
1 Introduction.	296
2 Therapeutic Potential of Endophytic Fungi	297
2.1 Anticancer Drugs.	299
2.2 Antibiotics.	299
2.3 Immune System Modulators.	299
2.4 Probiotics.	300
3 Endophytic Fungi as a Reservoir of Bioactive Substances.	300
3.1 Alkaloids.	300
3.2 Terpenoids.	308
3.3 Polyketide-Derived Lactones and Polyketides.	311
3.4 Peptides.	312
3.5 Quinones.	313
3.6 Saponins.	313
3.7 Flavonoids.	314
3.8 Fungal Endophyte-Derived Coumarins or Benzopyrones.	315
3.9 Lignans.	316
4 Investigating the Potential and Addressing Issues with the Use of Endophytes as Supplemental Sources of Natural Plant Extracts.	316
5 Endophytic Fungal Extracts and Plant Derivatives: Prospects for the Future.	317
6 Conclusion.	318
References.	318
15 Endophytic Fungi for Microbial Phytoremediation: Prospects for Agricultural and Environmental Sustainability.	325
Ratna Prabha, Dhananjaya P. Singh, Amrender Kumar, M. Kumar, Ritika, Shwetank Singh, Vishva Deepak Chaturvedi, and Rajan Singh	
1 Introduction.	326
2 Potential of Endophytic Fungi as Mycoremediators.	328
3 Different Pollutants and Mycoremediation.	332
4 Identification and Isolation of Endophytic Fungi with Mycoremediation Potential.	335
5 Advantages of Using Endophytic Fungi for Mycoremediation.	336
6 Factors Influencing the Activity of Endophytic Fungi in Mycoremediation.	337
7 Conclusion.	338
References.	338
Index.	347

Contributors

Charu Agnihotri Department of Agriculture and Environmental Sciences, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonipat, Haryana, India

Shekhar Agnihotri Department of Agriculture and Environmental Sciences, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonipat, Haryana, India

Vivek Ambastha Biology Department, Washington University in St. Louis, St. Louis, MO, USA

Awmpuizeli Department of Biotechnology/Life Sciences Pachhunga University College, Mizoram University, Aizawl, Mizoram, India

Kaizar J. Bharmal Institute of Chemical Technology Marathwada Campus, Jalna, Maharashtra, India

Pranav Bhaskar Department of Pharmacology, School of Medicine, University of Virginia, Charlottesville, VA, USA

Beirachhita Bohia Department of Biotechnology/Life Sciences Pachhunga University College, Mizoram University, Aizawl, Mizoram, India

Richa Bora Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Babli Borah Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Maini Borah Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Jyoti Lakshmi Hati Boruah Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Vishva Deepak Chaturvedi Department of Genetics and Plant Breeding, CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur, Kangra, Himachal Pradesh, India

Deepjyoti Das Natural Product Chemistry Group, Chemical Sciences and Technology Division, Jorhat, Assam, India

AcSIR- Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh, India

Mriganka Das Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

Mayuresh Dorle Department of Technology, Savitribai Phule Pune University, Ganeshkhind, Pune, Maharashtra, India

Arti Gaur Department of Life Sciences, Parul Institute of Applied Sciences, Parul University, Vadodara, Gujarat, India

Vibhav Gautam Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Navoneel Giri Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Parishmita Gogoi Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

AcSIR- Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh, India

Priyanka Gogoi Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

AcSIR- Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh, India

Upasana Goswami Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Rohit Prasad Gupta Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Divya Jain Department of Bioscience and Biotechnology, Banasthali Vidyapith, Banasthali, Rajasthan, India

Aman Jaiswal Department of Microbiology, College of Basic Sciences and Humanities, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

M. N. Jha Department of Microbiology, College of Basic Sciences and Humanities, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

Ojaswinin Kalita Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Swapnil C. Kamble Department of Technology, Savitribai Phule Pune University, Ganeshkhind, Pune, Maharashtra, India

Manveer Kaur Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Rajeev Kaushik Division of Microbiology, ICAR- Indian Agricultural Research Institute, New Delhi, India

Sibashish Kityania Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

Amrender Kumar Agricultural Knowledge Management Unit (AKMU), ICAR- Indian Agricultural Research Institute, New Delhi, India

Awnish Kumar Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Deepak Kumar Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Geeta Kumari Department of Microbiology, College of Basic Sciences and Humanities, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

Ketan Kumar Department of Biochemistry, School of Life Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India

M. Kumar ICAR-National Bureau of Agriculturally Important Microorganisms, Kushmaur, MauNath Bhanjan, Uttar Pradesh, India

Niraj Kumar Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

AcSIR- Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh, India

Rahul Kumar Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Rajiv Kumar Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

C. Lalbiaktluangi Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Nancy Lalhriatpuui Department of Biotechnology/Life Sciences Pachhunga University College, Mizoram University, Aizawl, Mizoram, India

Rosie Lalmuanpuui Department of Botany, Mizoram University, Aizawl, Mizoram, India

Felicia Lalremruati Department of Biotechnology/Life Sciences Pachhunga University College, Mizoram University, Aizawl, Mizoram, India

Lalrokimi Department of Biotechnology, Mizoram University, Aizawl, Mizoram, India

A. K. Lavanya ICAR-Central Research Institute for Jute and Allied Fibers, Barrackpur, Kolkata, West Bengal, India

Cecilia Lulu Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

AcSIR- Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh, India

Himanshu Mahawar ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh, India

Vishnu Mishra Delaware Biotechnology Institute, University of Delaware, Newark, DE, USA

Cheris Mistry Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Anish Nagar Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Mayur G. Naitam Department of Microbiology, College of Basic Sciences and Humanities, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

Deepa Nath Department of Botany, Guru Charan College, Silchar, Assam, India

Rajat Nath Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

Rupshikha Nath Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

Urvi R. Parlikar Institute of Chemical Technology Marathwada Campus, Jalna, Maharashtra, India

Ajit Kumar Passari Instituto de Investigaciones Biomédicas, Universidad Nacional Autónoma de México (UNAM), Ciudad de Mexico, México

Swati Patel Department of Plant Biotechnology, ASPEE Shakilam Biotechnology Institute, Navsari Agricultural University, Surat, Gujarat, India

Ratna Prabha Agricultural Knowledge Management Unit (AKMU), ICAR-Indian Agricultural Research Institute, New Delhi, India

Chandrabhan Prajapati Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Vijay Kumar Prajapati Department of Biochemistry, School of Life Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India

Ramannagari Visweswara Maruthi Prasad Department of Agriculture and Environmental Sciences, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonapat, Haryana, India

Rajneesh Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Abhishek Rao Department of Biochemistry, School of Life Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India

Ritika Agricultural Knowledge Management Unit (AKMU), ICAR-Indian Agricultural Research Institute, New Delhi, India

Ratul Saikia Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

AcSIR- Academy of Scientific and Innovative Research, Ghaziabad, Uttar Pradesh, India

Lovelesh Singh Saini Department of Life Sciences, Parul Institute of Applied Sciences, Parul University, Vadodara, Gujarat, India

Poorvi Saini Department of Biotechnology & Bioinformatics, School of Life Sciences, University of Hyderabad, Hyderabad, India

Rashmi Saini Department of Zoology, Gargi College, University of Delhi, Delhi, India

Joyita Sarkar Institute of Chemical Technology Marathwada Campus, Jalna, Maharashtra, India

Udita Sarkar Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Sai Sarvan Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Rashid Khalid Shaikh Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Apurva Singh Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Bhim Pratap Singh Department of Agriculture and Environmental Sciences, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonapat, Haryana, India

Dhananjaya P. Singh ICAR-Indian Institute of Vegetable Research, Varanasi, India

Prashant Kumar Singh Department of Biotechnology/Life Sciences Pachhunga University College, Mizoram University, Aizawl, Mizoram, India

Rajan Singh ICAR-Indian Institute of Vegetable Research, Varanasi, India

Santosh Kumar Singh Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Satyendra Singh Department of Biochemistry, School of Life Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India

Shwetank Singh Department of Plant Pathology, Acharya Narendra Dev University of Agriculture and Technology, Ayodhya, Uttar Pradesh, India

Vishal Kumar Singh Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Kunuthuru Sivakumar Department of Agriculture and Environmental Sciences, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonapat, Haryana, India

Reetesh Srivastava Faculty of Agricultural Sciences, Institute of Applied Sciences & Humanities, GLA University, Mathura, UP, India

Anupam Das Talukdar Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

Pooja Talukdar Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Harshita Tiwari Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Rahul Tiwari Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Viabhav Kumar Upadhyay Department of Microbiology, College of Basic Sciences and Humanities, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

Ashish Verma Centre of Experimental Medicine and Surgery, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India

Ashish Warghane School of Applied Sciences and Technology, Gujarat Technological University, Ahmedabad, Gujarat, India

Priti Warghane Graduate School of Pharmacy, Gujarat Technological University, Ahmedabad, Gujarat, India

Archana Yadav Biological Sciences & Technology Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam, India

Mukesh Kumar Yadav Department of Microbiology, Central University of Punjab, Bathinda, Punjab, India

Zirliangura Department of Chemistry, Government Zirtiri Residential Science College, Aizawl, Mizoram, India

Zothanpuia Department of Biotechnology/Life Sciences Pachhunga University College, Mizoram University, Aizawl, Mizoram, India

Chapter 1

Endophytic Fungi: Symbiotic Bioresource for Production of Plant Secondary Metabolites



Lovelesh Singh Saini, Swati Patel, Arti Gaur, Priti Warghane,
Rashmi Saini, and Ashish Warghane

Abstract Endophytes are a diverse group of microbes that asymptotically colonize the interior organs of higher plants. Fungi and bacteria are also considered endophytes, although the former is more common, adaptable, and pervasive microorganisms that colonize plants growing in practically all geoclimatic situations. Endophytic fungi are a kind of symbiotic fungus that lives inside the tissues of a plant. These fungi have a symbiotic relationship with the plant, providing nutrients and protection while receiving shelter and food from its host. Endophytic fungi can play a significant role in the sustainability of a plant species. Different strains of endophytic fungus are being researched, and the accompanying restrictions are being addressed for maximum use/multidimensional applications as beneficial metabolites with multifaceted environmental effects are progressively being discovered. The current chapter reveals that endophytic fungi are a chemical reservoir of novel compounds and elicit plant secondary metabolites with numerous applications in the pharmaceutical and agrochemical industries. Various bioactive metabolites produced by endophytic fungi have shown socioeconomic value and found uses in agriculture and the environment, as well as biofuels and biocatalysts.

L. S. Saini · A. Gaur

Department of Life Sciences, Parul Institute of Applied Sciences, Parul University,
Vadodara, Gujarat, India

S. Patel

Department of Plant Biotechnology, ASPEE Shakilam Biotechnology Institute, Navsari
Agricultural University, Surat, Gujarat, India

P. Warghane

Graduate School of Pharmacy, Gujarat Technological University, Ahmedabad, Gujarat, India

R. Saini

Department of Zoology, Gargi College, University of Delhi, Delhi, India

A. Warghane (✉)

School of Applied Sciences and Technology, Gujarat Technological University,
Ahmedabad, Gujarat, India

Keywords Endophytes · Plant secondary metabolites · Symbiotic relationship · Bioactive metabolites

1 Introduction

Higher plants provide complex, multilayered, diversified environments in spatial and temporal habitats that are home to assemblages of microorganisms of various species. Plants inside and outside their tissues contain many microorganisms, including bacteria, fungi, archaea, algae, and protists. Complex interactions between these species have progressively developed over a long-term, resulting in their symbiosis as a group rather than leaving them as separate species (Hassani et al. 2018). The interactions between these microbes and plants positively impact plant sustainability, biodiversity, and ecological stability (Rosier et al. 2016; Bai et al. 2017; Sasse et al. 2017).

Microorganisms, known as endophytes, inhabit plants for at least a portion of their life cycle without producing disease symptoms (Bacon and White 2000). Thus, “endophytism” is a special plant-microbe relationship defined by “location” (not “function”) that is momentarily symptomless, inconspicuous, and established within the living host plant tissues (Kusari and Spiteller 2012). Plants that possess poisonous alkaloids and interact with endophytes show high resistance to biotic and abiotic stresses (Carroll 1988; Chagas et al. 2018). Later on, a large body of evidence suggested that endophytic associations were crucial for the development of the plant immune system (Soliman et al. 2015), the control of disease (Terhonen et al. 2016), the uptake of nutrients (Hiruma et al. 2016), and to enhance the ability to withstand abiotic pressures (Khan et al. 2013).

In the accumulations of plants and microbes, microfungi predominate, colonizing the surfaces of leaves and twigs (epiphytes), the tissues inside leaves (foliar endophytes), the young and old bark (bark endophytes), and the wood (xylem endophytes and wood decomposers) (Stone et al. 2004). Endophytic fungus is highly varied and polyphyletic; it includes organisms that can live asymptotically in the above- and belowground tissues of plants and play a wide range of ecological tasks (Saikkonen et al. 1998). Numerous endophytes can produce a range of bioactive compounds that may be employed directly or indirectly as therapeutic agents against a variety of ailments (Strobel et al. 2004; Staniek et al. 2008; Aly et al. 2010; Kharwar et al. 2011; Kusari and Spiteller 2012; Passari et al. 2015, 2016). Additionally, a large number of endophytic fungi are sources of cytotoxic compounds and secondary metabolites that are biologically active, like paclitaxel, podophyllotoxin, deoxypodophyllotoxin, camptothecin, hypericin, emodin, and azadirachtin (Stierle et al. 1993; Eyberger et al. 2006; Puri et al. 2005, 2006; Kusari et al. 2008, 2009, 2012; Shweta et al. 2010). Various coniferous and deciduous tree hosts for endophytic *Pezizula* species strains produce bioactive secondary

metabolites in culture (Noble et al. 1991; Schulz et al. 1995). Cytochalasins and indole diterpenes with significant biological activity are commonly produced by endophytic species of the *Xylariaceae* (Brunner and Petrini 1992).

Endophyte synthesis of bioactive substances, mainly those unique to their host plants, is significant from a biochemical, pharmacological, and ecological standpoint. Exciting opportunities exist to use endophytic fungus to produce a wide range of recognized and undiscovered physiologically active secondary metabolites.

2 Evolution of Endophytic Fungi in Plants

Endophytic fungi, which dwell inside plant tissues permanently or for a specific time during their life cycles, colonize plants, especially perennials (Stone et al. 2004; Demain 2014), causing no apparent harm or morphological alterations. These microorganisms typically coexist alongside diseases and comprise fungi and bacteria (Zhang et al. 2006; Gouda et al. 2016). In plant tissues, fungal endophytes exist internally, intercellularly or intracellularly, and asymptotically. Endophytes are distinguishable from mycorrhizae by missing external hyphae or mantels, and they often reside in aboveground plant tissues but can also occasionally be found in roots. Over the past 10 years, the definition of “endophyte” has undergone several changes (Sinclair and Cerkaskas 1996; Bills 1996; Saikkonen et al. 1998).

Parasitic or pathogenic fungi are believed to have originated endophytes on both grasses and woody plants (Carroll 1986, 1991, 1992). Woody plant endophytes are closely related to pathogenic fungi and are thought to have descended from them by lengthening their latency periods and decreasing their pathogenicity (Petrini et al. 1992). It is also believed that the fungal grass diseases of the genus *Epichloe* are the ancestors of the *Neotyphodium* grass endophytes. But there doesn't seem to be a clear coevolutionary route between the host plant and the endophyte. Plants have faced a variety of abiotic and biotic stressors throughout evolution. Since they cannot move, plants have relied on vegetative growth, sophisticated physiology, and seed dissemination to avoid or lessen stress's effects. All plants are known to sense signals, transfer them, and react to stresses, including disease, salt, heat, and drought (Bohnert et al. 1995; Bartels and Sunkar 2005).

Surprisingly complex microscopic specimens have been found in the Canadian Arctic. The earliest documented appearance of fungus may have occurred around 1 billion years ago, more than 500 million years earlier than previously thought, according to tiny fossils discovered in remote Arctic Canada. Endophytes have developed unique biotransformation skills due to the long-term coevolution of fungal endophytes and host plants, which can significantly affect the metabolism and makeup of plants.

Geographical considerations, interactions with other species in the community, phylogenetic and life history restrictions, and abiotic factors all affect the continuum of antagonistic-mutualistic interactions between any two interacting species (Thompson and Pellmyr 1992; Thompson 1994). Similar to this, even during the

life span of the microbe and host plant, complex microbial mutualisms with host plants fluctuate along a continuum from pathogenic to mutualistic (Sinclair and Cerkaskas 1996). Although endophytic fungal-host plant interactions are complex and variable, evolutionary traits like mode of transmission and infection patterns as well as ecological factors like host condition, competition with other microorganisms, population structure, and prevailing abiotic factors allow predictions of where endophyte-plant associations are likely to fall along the continuum.

The byproducts of main metabolic pathways are termed primary metabolites, encompassing lipids, proteins, carbohydrates, and amino acids. They are crucial to the metabolism of building blocks and an organism's growth. Without them, the organism's growth and development are very likely to have flaws. The fact that the by-products of several crucial stages serve as precursors for producing secondary metabolites is an essential function of basic metabolism. These precursors are used by both endophytes and their host plants in their separate secondary metabolites (SMs) biosynthesis processes. According to Kirby and Keasling (2009) and Deepika et al. (2016), SMs in EFs may imitate the host pathways and use those pathways as their biosynthetic route. Using blocking mutant and radiolabeling approaches, researchers have explored the synthesis of certain phytochemicals, including ergot alkaloids, aflatoxin, and lovastatin (Keller et al. 2005; Rekadwad et al. 2022). Although varied, a few shared biosynthetic pathways synthesize SMs, and endophytic fungal communities and their host plants' metabolomic pathways are comparable. It is unclear whether these low-molecular-weight phytochemicals are produced by plants directly or through symbiosis with microbes inside them.

3 Biodiversity of Endophytic Fungi

Nearly every plant on the earth has endophytes, which are the most distinctive microbes. It has mainly been extracted from the soil of large and small trees, coastal grasses, and lichens. Many different microbes, such as bacteria, actinobacteria, fungi, and algae, are found inside the plant tissue (Saini et al. 2015; Zhang et al. 2018; Passari et al. 2020; Sriravali et al. 2022). They all establish symbiotic or asymbiotic biological relationships with the host-plant body. Prokaryotic cells connected with plants through vertical or horizontal transmission through stomata and colonizing the internal plant tissue make up the wide endophytic variety in our ecosystem. Endophytic microorganisms target various parts of the host-plant body, so they can enter and establish a habitat.

Fungal endophytes are a common type of endophyte. Endophytic fungi can sustainably increase crop output and growth by enduring severe biotic and abiotic stress conditions, including drought, high temperatures, and salinity (Rodriguez et al. 2009). Due to their extensive adaption, the fungal endophytes colonize the plant tissue's intra- and intercellular regions, forming a symbiotic or mutualistic

relationship with the host (Aly et al. 2011). The host plant provides the fungal strain with food and protection, and the fungal endophyte confers resistance to pathogens and numerous abiotic stresses. The transfer of a fungal cell to a damaged wound region through surface contact or channels is called external fungal endophytes. Endogenous fungal endophytes, however, travel through inner organelles like mitochondria and chloroplasts (Yadav 2020). There are two ways that fungal endophytes can spread: vertically or systemically from the host plant body to the offspring or seeds of the host plant or horizontally or nonsystematic through sexual reproduction or infection (Malik et al. 2023).

Endophytic fungi belong to diverse phyla, including Ascomycota, Basidiomycota, and Mucoromycota. The majority of endophytic fungi belong to Ascomycota (89%), followed by Basidiomycota (9%), and the remaining to Mucoromycota (2%) (Rana et al. 2019). The diversity of fungal endophyte species in these phyla is summarized in Table 1.1.

The variety of all fungal endophytes can be divided into two major groups. These include *Clavicipitaceae* (CE), which are widely dispersed and occur in asymptomatic tissues of nonvascular plants, conifers, ferns, and angiosperms, which infect specific grasses restricted to chilly climates and nonclavicipitaceous endophytes (NCE). NCE, however, is reportedly only found in the Ascomycota and Basidiomycota groups (Maldonado-González et al. 2015). On every continent, fungi have been found to colonize terrestrial plants. They have been isolated from ferns, gymnosperms, angiosperms, arctic habitats, tropical climes, various xeric environments, and boreal woods (Suryanarayanan et al. 2000; Mohali et al. 2005; Šraj-Kržič et al. 2006; Selim et al. 2017).

Different fungal species with a variety of chemical productions are found in the various fungal areas of plants. A study of the microbial diversity in *Paris polyphylla* var. *yunnanensis* plants (Liu et al. 2017) found that *Trichoderma viride* and *Leptodontidium* sp. coexisted with the dominating species *Fusarium oxysporum* in the rhizospheric endophytes. Along with these three predominant fungi, the presence of *Alternaria* sp., *Pyrenochaeta* sp., *Truncatella* sp., *T. viride*, *Chaetomium* sp., *Penicillium swiecickii*, and *Cylindrocarpon* sp. was also noted.

4 Interaction of Endophytic Fungi with Host Plant

Filamentous fungus and vesicular–arbuscular mycorrhiza (VAM) are the most paramount groups included and investigated as endophytes. Certain fungi that belong to the genus *Trichoderma*, *Colletotrichum*, *Penicillium*, *Aspergillus*, *Purpureocillium*, *Fusarium*, *Claviceps*, *Metarhizium*, *Xylaria*, *Curvularia*, *Cladosporium*, *Dreschlera*, *Alternaria*, etc. colonizes either roots, shoots, or leaves (Uzma et al. 2018; Attia et al. 2020; Baron and Rigobelo 2021). They are populating in the endosphere of plants and are transmitted horizontally or vertically. Endophytes can uphold in

Table 1.1 Biodiversity of different groups of endophytic fungi associated with different hosts

Phyla	Species	References
Ascomycota	<i>Curvularia</i> sp., <i>Setosphaeria</i> sp., <i>Guehomyces</i> sp., <i>Annulohypoxyton</i> sp., <i>Trichoderma</i> sp., <i>Xylaria</i> sp., <i>Septoria</i> sp., <i>Trichosporon</i> sp., <i>Filobasidium</i> sp., <i>Mucor</i> sp., <i>Neurospora</i> sp., <i>Ampelomyces</i> sp., <i>Microdochium</i> sp., <i>Helminthosporium</i> sp., <i>Tilletiopsis</i> sp., <i>Anthostomella</i> sp., <i>Ophiocordyceps</i> sp., <i>Plectosphaerella</i> sp., <i>Emericella</i> sp., <i>Talaromyces</i> sp., <i>Glomus</i> sp., <i>Stagonospora</i> sp., <i>Gibberella</i> sp., <i>Alternaria</i> sp., <i>Cryptococcus</i> sp., <i>Nectria</i> sp., <i>Sordariomycetes</i> sp., <i>Ilyonectria</i> sp., <i>Davidella</i> sp., <i>Chaetomium</i> sp., <i>Rhodosporeidium</i> sp., <i>Eurotium</i> sp., <i>Stemphylium</i> sp., <i>Didymella</i> sp., <i>Rigidoporus</i> sp., <i>Bipolaris</i> sp., <i>Coniothyrium</i> sp., <i>Ulocladium</i> sp., <i>Cercospora</i> sp., <i>Engyodontium</i> sp., <i>Porostereum</i> sp., <i>Paraconiothyrium</i> sp., <i>Phaeosphaeria</i> sp., <i>Boeremia</i> sp., <i>Cochliobolus</i> sp., <i>Exserohilum</i> sp., <i>Calonectria</i> sp., <i>Paraphoma</i> sp., <i>Diaporthe</i> sp., <i>Eutypella</i> sp., <i>Cladophialophora</i> sp., <i>Macrophomina</i> sp., <i>Rhizopus</i> sp., <i>Phaeosphaeriopsis</i> sp., <i>Corynespora</i> sp., <i>Nigrospora</i> sp., <i>Lasiodiplodia</i> sp., <i>Wallemia</i> sp., <i>Paecilomyces</i> sp., <i>Puccinia</i> sp., <i>Williopsis</i> sp., <i>Lecanicillium</i> sp., <i>Leptosira</i> sp., <i>Fusarium</i> sp., <i>Nemania</i> sp., <i>Neofusicoccum</i> sp., <i>Dichotomopilus</i> sp., <i>Cylindrocarpum</i> sp., <i>Leptosphaeria</i> sp., <i>Aspergillus</i> sp., <i>Pleosporales</i> sp., <i>Peyronellaea</i> sp., <i>Marasmius</i> sp., <i>Crinipellis</i> sp., <i>Mortierella</i> sp., <i>Eupenicillium</i> sp., <i>Bipolaris</i> sp., <i>Clonostachys</i> sp., <i>Phomopsis</i> sp.	Sieber et al. (1988), Fisher and Petrini (1992), Larran et al. (2001), Wakelin et al. (2004), Tian et al. (2004), Nassar et al. (2005), Pan et al. (2008), Saunders and Kohn (2008), Naik et al. (2009), Yuan et al. (2010), Khan et al. (2011, 2012), Gao et al. (2011, 2012), de Souza Leite et al. (2013), Tenguria and Firodiya (2013), Impullitti and Malvick (2013), Amin (2013), Zhao et al. (2012, 2013, 2014), Tian et al. (2014), Fernandes et al. (2015), Colla et al. (2015), Gonzaga et al. (2015), Köhl et al. (2015), Chadha et al. (2015), Pierre et al. (2016), Marcenaro and Valkonen (2016), dos Santos et al. (2016), Parsa et al. (2016), Keyser et al. (2016), Ofek-Lalzar et al. (2016), Wang et al. (2016), Renuka and Ramanujam (2016), Bogner et al. (2016), Rothen et al. (2017), Potshangbam et al. (2017), Hamayun et al. (2017), Singh and Gaur (2017), Spagnoletti et al. (2017), Narayan et al. (2017), Comby et al. (2017), Larran et al. (2002, 2007, 2018), Yang et al. (2014a, 2018), Zhao et al. (2018), Xing et al. (2018), and Rana et al. (2019)
Basidiomycota	<i>Cryptococcus</i> sp., <i>Trichosporon</i> sp., <i>Puccinia</i> sp., <i>Porostereum</i> sp., <i>Rigidoporus</i> sp., <i>Filobasidium</i> sp., <i>Rhodotorula</i> sp., <i>Guehomyces</i> sp., <i>Tilletiopsis</i> sp., <i>Crinipellis</i> sp., <i>Marasmius</i> sp., <i>Wallemia</i> sp., <i>Rhodosporeidium</i> sp., <i>Sporobolomyces</i> sp., <i>Cryptococcus</i> sp., <i>Cystobasidium</i> sp., <i>Sporobolomyces</i> sp., <i>Rhizoctonia</i> sp.	
Mucoromycota	<i>Glomus</i> sp., <i>Mucor</i> sp., <i>Mortierella</i> sp.	

environments like high temperatures, temperate forests, mangrove forests, and tropical forests (Arnold 2008), insinuating they can survive under diverse climatic conditions. Endophytic fungi are distinct in their colonization due to the expression of genes required for the molecules necessitated for their colonization. However, there are the least details available for the accountable genes (Behie and Bidochka 2014). It can enter the plant system via wounding of plant tissues that further secrete nutrient metabolites and chemoattractants of endophytes. There is the germination of fungal mycelia in roots and its extensive penetration into the root cortex. Thereby, it commences its colonization. It spreads through the cell wall to the adjacent cells of plants and moves further in the plant system (Yan et al. 2019). Endophytes are observed in almost all plant parts, such as root, shoot, stem, leaves, and reproductive tissues. The existence of endophytes is validated via surface sterilization of plant tissue followed by its growth on a specific media or with metagenome analysis. The internal parts of the plant are the protective, secure zones for the endophytic fungus to get the required nourishment and ameliorate competition. In turn, the fungi also favor plants through direct and indirect courses. They benefit plants directly with nutrient acquisition, secreting molecules that facilitate plant growth. Indirectly with the production of important secondary metabolites and other compounds, endophytic fungus protects plants from biotic and abiotic stress (Fig. 1.1).

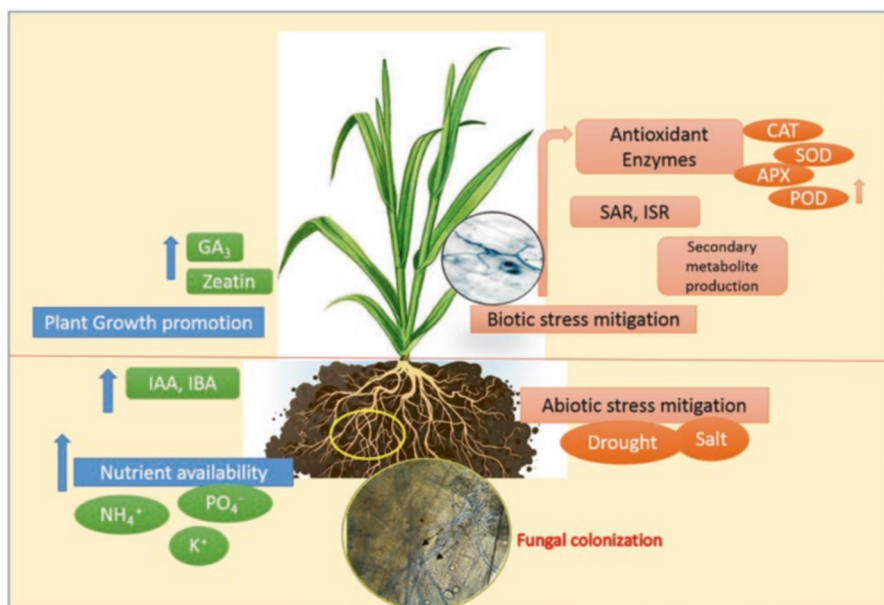


Fig. 1.1 Direct and indirect benefits offered by endophytic fungal colonization. Parameters in blue and green boxes show the direct effects of plant growth promotion. Pink and orange boxes indicate the indirect use of biotic and biotic stress tolerance to the colonized plant

4.1 For Sustainable Agriculture

A global climate change concern is due to deforestation, domestication, urbanization, soil salinization, and soil pollution through the extensive use of chemical fertilizers and pesticides. Plants are also losing important valuable microorganisms due to the abovementioned situations. Therefore, they are not acquiring the direct and indirect advantages imparted by them, which makes them more resistant to stress.

Nutrient Availability

Endophytes do have a role in facilitating macroelements (nitrogen, potassium, phosphorous, calcium, magnesium, sulfur) and microelements (zinc, iron, copper, etc.) for the plants, which make efficient use of fertilizers applied. They can also play a role as biofertilizers. The first report of colonization by the endophytic fungus *Piriformospora indica* revealed that external hyphae of the fungus possess phosphate transporter (*PiPT*) expression that helps to absorb phosphate and make it available to maize plants. Mycorrhizal fungi *Metarhizium* and *Beauveria* have been reported to augment the availability of nitrogen and phosphorous in their symbiosis (Behie and Bidochka 2014). Under conditions of low nitrogen, the genes associated with nitrogen uptake and metabolism, including *OSAMT1;1*, *OSAMT2;2*, *OSNR1*, and *OSGS1*, are upregulated in rice due to endophytic colonization by *Phomopsis liquidambari*. This upregulation is accompanied by elevated levels of total nitrogen, amino acids, proteins, and free NH_4^+ (Yang et al. 2014b).

Plant Growth Promotion

Phytohormone production is also characteristic of many endophytic fungi. They can produce auxin, cytokinin, and gibberellic acid, mainly with siderophore (Mishra et al. 2016; Tothhawng et al. 2019; Abdalla et al. 2020). The endophytic fungi *Aspergillus fumigatus* TS1 and *Fusarium proliferatum* symbionts of *Oxalis corniculata* roots have been screened to have indole acetic acid production and siderophore production with an eclectic derivative of gibberellic acid, such as GA_1 , GA_3 , and GA_7 (Bilal et al. 2018). Endophytic fungus belongs to the genus *Fusarium*, *Alternaria*, *Xylogone*, and *Didymella* isolated from a medicinally important plant *Sophora flavescens* found to produce a significant concentration of IAA (indole acetic acid), and it has been proven with application and observation of primary root length in *Arabidopsis* plant (Turbat et al. 2020). Endophytic colonization in root cortical cells with *Chaetomium globosum* strain ND35 fostered the growth of cucumber plants with the production of hormones zeatin, gibberellic acid, indole-3 acetic acid (IAA), and indole butyric acid (IBA) (Tian et al. 2022).